The Effects of Process RD in an Asymmetric Duopoly under Cournot and Supply Function Competitions

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Abstract. In this paper we attempt to explore the welfare effects of (process) R&D in an asymmetric duopoly with a homogeneous product under Cournot and supply function competitions. To this aim, we consider a two-stage perfect-information game where the duopolists compete in stage one in R&D investments and in stage two either in quantities or in supply functions. Calculating the (subgame-perfect Nash) equilibrium of this game numerically for a wide range of initial cost parameters and comparing it to the equilibrium with no R&D, we show that R&D has a positive effect on the welfares of consumers and the society as a whole. While its effect on the profits of the duopolists is also positive under the Cournot competition, it becomes negative under the supply function competition. This latter negative effect is caused by the duopolists' more aggressively investing in R&D under the supply function competition, increasing the industry output, and consequently decreasing the product price, to a harmful level for themselves. Moreover, we show that R&D always widens up the efficiency gap between the duopolists under the supply function competition, while narrowing it down under the Cournot competition.

Keywords: Duopoly; Cournot competition; supply function competition; process R&D

JEL Codes: D43; L13

1 Introduction

In this paper we consider a homogeneous-product duopoly with cost asymmetry to explore the welfare effects of process (cost-reducing) R&D when the duopolists compete in either supply functions or (fixed) quantities. To the best of our knowledge, the welfare effects of (any type of) R&D under the supply function competition have not been studied before. On the other hand, the welfare effects of R&D under the quantity competition of Cournot (1838) and under the price competition of Bertrand (1883) have been extensively studied by many works in the oligopoly literature. A fundamental question investigated by most of these works is whether the celebrated results of Singh and Vives (1984) and Vives (1985) about the superiority of the Bertrand competition over the Cournot competition in terms of efficiency (in consumer surplus and total surplus) remains to hold when the duopolistic firms compete in process or product R&D prior to production. A somewhat surprising answer to this question was obtained by Qiu (1997), showing that in a differentiated duopoly with process R&D, the Cournot competition in the output market always induces a higher R&D effort than the Bertrand competition, while the outcome of the Cournot competition can become more efficient than the outcome of the Bertrand competition if the duopolistic products are close substitutes and R&D productivity as well as spillovers in the output of R&D are sufficiently high. In fact, the same results were later shown to also hold when the R&D competition model of Qiu (1997) is modified to involve product R&D (as in Symeonidis, 2013) instead of process R&D or modified to involve input spillovers in R&D (as in Hinloopen and Vandekerckhove, 2009) instead of output spillovers.

In our model, we consider process R&D as in Qiu (1997) and Hinloopen and Vandekerckhove (2009). However, unlike these two works, we allow for neither spillovers in R&D nor differentiation in the output market. Moreover, we consider the supply function competition in the output market in comparison to the Cournot competition. To give more details, we model the R&D and production process as a two-stage perfect-information game where the duopolists non-cooperatively choose in the first stage their R&D investments and in the second stage either their supply functions or their quantities. Calculating the subgame-perfect Nash equilibrium (Selten, 1965) of this game numerically for a wide range of initial cost parameters and comparing it to the equilibrium with no R&D, we show that R&D has always a positive effect on the welfares of consumers and the society as a whole. While its effect on the profits of the duopolists is also positive under the Cournot competition, it becomes negative under the supply function competition. This latter negative effect is caused by the duopolists' more aggressively investing in R&D under the supply function competition, increasing the industry output, and consequently decreasing the product price, to a harmful level for themselves. Moreover, we show that R&D always widens up the efficiency gap between the duopolists under the supply function competition, while narrowing it down under the Cournot competition.

Besides the welfare effects of R&D, our results also involve a welfare comparison between the supply function competition and the Cournot competition with and without R&D. However, we should note that a welfare comparison between these two competitions in the absence of R&D has previously been provided by Saglam (2008a) and (2008b) in different settings. Unlike our paper, both of these works consider a symmetric duopoly and they both allow uncertainty about demand. Saglam (2008a) shows that when the duopolists produce a single homogeneous product the supply function competition can Pareto dominate the Cournot competition if and only if the size of demand uncertainty is sufficiently large, whereas Saglam (2008b) finds that under product differentiation the dominance relation in Saglam (2008a) remains to hold irrespective of the size of demand uncertainty if the degree of product substitution is extremely low. On the other hand, our paper shows that in the absence of R&D, the supply function competition is always Pareto superior to the Cournot competition over the whole ranges of cost parameters in our simulations. Moreover, this Pareto ranking is not affected by the presence of process

R&D.

The rest of the paper is organized as follows: In Section 2, we present our model. Section 3 contains our results and Section 4 concludes.

2 Model

We consider a duopolistic industry where a single homogeneous good is produced under cost asymmetry. Firm $i = 1, 2$ faces the cost function

$$C_i(q_i) = c_i(x_i)q_i^2/2, \tag{1}$$

where q_i is the quantity produced by firm i and $c_i(x_i) > 0$ is its unitary marginal cost that is affected by the variable $x_i \geq 0$, denoting the investment in process R&D (hereafter, simply R&D) by firm i. We assume that the common R&D technology of the firms is such that for each $i = 1, 2$

$$c_i(x_i) = c_{i,0}\, exp(-x_i), \tag{2}$$

where $x_i \geq 0$ and $c_{1,0} < c_{2,0}$, i.e., before any R&D takes place in the industry, firm 1 has a lower unitary marginal cost than firm 2. (Therefore, in many places firms 1 and 2 will be simply called the efficient and inefficient firms, respectively.) Also note that the technology in (2) implies no R&D spillovers, i.e., for any $i, j \in \{1, 2\}$ with $j \neq i$, $\partial c_i(x_i)/\partial x_j = 0$.

Investing in R&D is costly for each firm. Any firm investing in $x \geq 0$ units of R&D incurs a quadratic cost (as in d'Aspremont and Jacquemin, 1988):

$$z(x) = \delta x^2/2, \tag{3}$$

where δ is a parameter that is positive. Note that according to (3), the marginal cost of R&D is increasing and independent of the size of the firm. Finally, we assume that the demand curve faced by the duopolistic firms is given by

$$D(p) = a - bp, \tag{4}$$

where $a, b > 0$ are the intercept and slope parameters and $p \in [0, a/b]$ denotes the product price. Equations (1)-(4) as well as the parameters $c_{1,0}, c_{2,0}$, δ, a, and b are common knowledge.

3 Results

For the duopolistic industry described above, we will consider a two-stage perfect-information game where the duopolistic firms non-cooperatively determine their R&D investments in stage one and then non-cooperatively determine their outputs, and consequently the market price, in stage two. Using backwards induction, we will solve this game starting from the second stage where both firms will have strategies in supply functions or strategies in fixed quantities. Using the equilibrium strategies calculated for the second stage, we will then solve the equilibrium of the R&D competition in the first stage.

3.1 Supply Function Competition with R&D Investment

Here, we will consider the case where the duopolistic firms compete in supply functions in the second stage game.[1] Formally, a stage-two strategy for firm $i = 1, 2$ is a linear function mapping prices into quantities, i.e., $S_i = \eta_i p$ where $\eta_i \geq 0$. Given the strategies S_1 and S_2, the duopolistic product market clears if

$$D(p) = S_1(p) + S_2(p) \tag{5}$$

or

$$a - bp = \eta_1 p + \eta_2 p, \tag{6}$$

implying an equilibrium price $p^{SF}(\eta_1, \eta_2) \equiv p^{SF}(\eta_2, \eta_1)$, given by

$$p^{SF}(\eta_1, \eta_2) = \frac{a}{b + \eta_1 + \eta_2}. \tag{7}$$

A pair of supply functions $(S_1^*(p), S_2^*(p)) = (\eta_1^* p, \eta_2^* p)$ forms a Nash (1950) equilibrium if for each $i, j \in \{1, 2\}$ with $j \neq i$ the function $S_i^*(p)$ maximizes the expected profits of firm i when firm j produces according to the function $S_j^*(p)$. That is, $(\eta_1^* p, \eta_2^* p)$ forms a Nash (1950) equilibrium if for each $i, j \in \{1, 2\}$ with $j \neq i$ the parameter η_i^* solves

$$\max_{\eta_i \geq 0} p^{SF}\left(\eta_i, \eta_j^*\right) S_i^*\left((p(\eta_i, \eta_j^*)\right) - \frac{c_i(x_i)}{2} S_i^*(p(\eta_i, \eta_j^*))^2 - z(x_i), \tag{8}$$

or explicitly

$$\max_{\eta_i \geq 0} \left(\eta_i - \frac{c_i(x_i)\eta_i^2}{2}\right)\left(\frac{a}{b + \eta_i + \eta_j^*}\right)^2 - z(x_i). \tag{9}$$

Proposition 1. *Given the R&D levels x_1 and x_2 determined in the first stage of the duopolistic game, the stage-two competition in linear supply functions has a unique Nash equilibrium characterized by $S_i^{SF}(p) = \eta_i^{SF}(x_i, x_j)p$ for each $i, j \in \{1, 2\}$ with $j \neq i$, where*

$$\eta_i^{SF}(x_i, x_j) = \frac{2}{c_i(x_i) + \sqrt{c_i(x_i)^2 + \frac{4}{b}\left(\frac{c_i(x_i) + c_j(x_j) + bc_i(x_i)c_j(x_j)}{2 + bc_j(x_j)}\right)}}. \tag{10}$$

Proof. If the pair of supply functions $\langle \eta_1^{SF}(x_1, x_2)p, \eta_2^{SF}(x_2, x_1)p \rangle$ forms a Nash (1950) equilibrium, then for each $i, j \in \{1, 2\}$ with $j \neq i$ the price $p^{SF}\left(\eta_1^{SF}(x_1, x_2), \eta_2^{SF}(x_2, x_1)\right)$ must solve

$$\max_{p \geq 0} p\left(a - bp - S_j^{SF}(p)\right) - \frac{c_i(x_i)}{2}\left(a - bp - S_j^{SF}(p)\right)^2 - z(x_i). \tag{11}$$

[1] The supply function competition model we consider here is an adaptation of the symmetric oligopoly model of Klemperer and Meyer (1989) to an asymmetric duopoly, like in Green (1999). However, we cannot borrow our related characterization result (Proposition 1) from Green (1999), as he did not need to explicitly characterize the equilibrium supply functions.

The first-order necessary condition for the above maximization implies

$$\begin{aligned} 0 &= \left(a - bp - S_j^{SF}(p)\right) \\ &\quad + \left(p - c_i(x_i)\left(a - bp - S_j^{SF}(p)\right)\right)\left(-b - \frac{\partial S_j^{SF}(p)}{\partial p}\right), \end{aligned} \tag{12}$$

or

$$\begin{aligned} 0 &= S_i^{SF}(p) + \left(p - c_i(x_i)S_i^{SF}(p)\right)\left(-b - \eta_j^{SF}(x_j, x_i)\right) \\ &= \eta_i^{SF}(x_i, x_j)p + \left(p - c_i(x_i)\eta_i^{SF}(x_i, x_j)p\right)\left(-b - \eta_j^{SF}(x_j, x_i)\right), \end{aligned} \tag{13}$$

implying

$$\eta_i^{SF}(x_i, x_j) = \frac{b + \eta_j^{SF}(x_j, x_i)}{1 + c_i(x_i)(b + \eta_j^{SF}(x_j, x_i))}. \tag{14}$$

Let $\eta_i^{SF} \equiv \eta_i^{SF}(x_i, x_j)$ and $\eta_j^{SF} \equiv \eta_j^{SF}(x_j, x_i)$. Then, equation (14) implies

$$\frac{1}{\eta_i^{SF}} = \frac{1}{b + \eta_j^{SF}} + c_i(x_i) \tag{15}$$

and

$$\frac{1}{\eta_j^{SF}} = \frac{1}{b + \eta_i^{SF}} + c_j(x_j). \tag{16}$$

Define $E_i = 1/\eta_i^{SF}$ and $E_j = 1/(b + \eta_j^{SF})$. Then, (15) and (16) imply

$$E_i = E_j + c_i(x_i) \tag{17}$$

and

$$\frac{1}{\frac{1}{E_j} - b} = \frac{1}{\frac{1}{E_i} + b} + c_j(x_j). \tag{18}$$

Inserting (17) into (18) and with the help of some arrangements we obtain

$$\frac{E_j}{1 - bE_j} = \frac{(1 + bc_j(x_j))E_j + c_i(x_i) + c_j(x_i) + bc_i(x_i)c_j(x_j)}{1 + bE_j + bc_i(x_i)}. \tag{19}$$

It follows from (19) that

$$E_j^2 + c_i(x_i)E_j - \frac{c_i(x_i) + c_j(x_j) + bc_i(x_i)c_j(x_j)}{b(2 + bc_j(x_j))} = 0. \tag{20}$$

The positive-valued solution to the above quadratic equation can be calculated as

$$E_j = \frac{-c_i(x_i) + \sqrt{c_i(x_i)^2 + \frac{4}{b}\left(\frac{c_i(x_i) + c_j(x_j) + bc_i(x_i)c_j(x_j)}{2 + bc_j(x_j)}\right)}}{2}. \tag{21}$$

Then using (17) and $E_i = 1/\eta_i^{SF}$, we obtain (10). To check the second-order sufficiency condition, we differentiate the right-hand side of (12) with respect to p to obtain $(-b - \eta_j^{SF}(x_j, x_i)) + (1 + c_i(x_i)(b + \eta_j^{SF}(x_j, x_i)))(-b - \eta_j^{SF}(x_j, x_i)) < 0$ for all $p \geq 0$. So, $p^{SF}(\eta_1^{SF}(x_1, x_2), \eta_2^{SF}(x_2, x_1))$ solves the problem in (11), implying that the supply functions $\eta_1^{SF}(x_1, x_2)p$ and $\eta_2^{SF}(x_2, x_1)p$ form a Nash equilibrium in the second-stage game. $\square$

Define $p^{SF}(x_1, x_2) \equiv p^{SF}\left(\eta_1^{SF}(x_1, x_2), \eta_2^{SF}(x_2, x_1)\right)$ for any x_1 and x_2. Note that $q_1^{SF}(x_1, x_2) = \eta_1^{SF}(x_1, x_2)\, p^{SF}(x_1, x_2)$ and $q_2^{SF}(x_2, x_1) = \eta_2^{SF}(x_2, x_1)\, p^{SF}(x_1, x_2)$. Perfectly anticipating the equilibrium supply functions that would be chosen in the second stage of the duopolistic game, firm i can calculate in the first stage its profits $\pi_i^{SF}(x_i, x_j)$, at each possible investment pair (x_i, x_j) where $j \neq i$, as follows:

$$\pi_i^{SF}(x_i, x_j) \quad = \quad p^{SF}(x_i, x_j)\, q_i^{SF}(x_i, x_j) - \frac{c_i(x_i)}{2} q_i^{SF}(x_i, x_j)^2 - z(x_i) \tag{22}$$

We say that a pair of R&D investment strategies (x_1^{SF}, x_2^{SF}) forms a Nash equilibrium of the reduced game in stage one if for each $i, j \in \{1, 2\}$ with $j \neq i$, x_i^{SF} maximizes the expected profits of firm i when firm j invests x_j^{SF}. That is, for each $i, j \in \{1, 2\}$ with $j \neq i$, the R&D level x_i^{SF} solves

$$\max_{x_i \geq 0} \quad \pi_i^{SF}(x_i, x_j^{SF}). \tag{23}$$

Given an equilibrium (x_1^{SF}, x_2^{SF}), involving the solution to (23) for each firm, it follows that the strategy profile $\langle (x_1^{SF}, x_2^{SF}), (\eta_1^{SF}(x_1^{SF}, x_2^{SF}), \eta_2^{SF}(x_2^{SF}, x_1^{SF})) \rangle$ constitutes a subgame-perfect Nash equilibrium of the two-stage game played by the duopolists. At this equilibrium, the profits obtained by firm i become

$$\begin{aligned} \pi_i^{SF}(x_i^{SF}, x_j^{SF}) \quad &= \quad \eta_i^{SF}\left(x_i^{SF}, x_j^{SF}\right) p^{SF}\left(x_i^{SF}, x_j^{SF}\right)^2 \\ &\quad - \frac{c_i\left(x_i^{SF}\right)}{2} \eta_i^{SF}\left(x_i^{SF}, x_j^{SF}\right)^2 p^{SF}\left(x_i^{SF}, x_j^{SF}\right)^2 - \frac{\delta}{2}\left(x_i^{SF}\right)^2. \end{aligned} \tag{24}$$

Let $Q^{SF}(x_1, x_2) \equiv q_1^{SF}(x_1, x_2) + q_2^{SF}(x_2, x_1)$. Then the equilibrium consumer surplus becomes

$$\begin{aligned} CS^{SF}(x_1^{SF}, x_2^{SF}) \quad &= \quad \frac{Q^{SF}\left(x_1^{SF}, x_2^{SF}\right)^2}{2b} \\ &= \quad \frac{\left[\eta_1^{SF}(x_1^{SF}, x_2^{SF}) + \eta_2^{SF}(x_2^{SF}, x_1^{SF})\right]^2 p^{SF}(x_1^{SF}, x_2^{SF})^2}{2b}. \end{aligned} \tag{25}$$

We leave the calculation of x_i^{SF} and x_j^{SF} as well as the corresponding equilibrium outputs and welfares to Section 3.3.

3.2 Cournot Competition with R&D Investment

Here, we assume that the duopolistic firms compete in quantities in the second stage game. Formally, a stage-two strategy for firm $i = 1, 2$ is a fixed quantity $q_i \geq 0$. Given strategies q_i and q_j chosen by firms

i and j, the product market clears at a price $p^C(q_i, q_j)$ if

$$D(p^C(q_i, q_j)) = q_i + q_j, \tag{26}$$

implying

$$p^C(q_i, q_j) = \frac{a - q_i - q_j}{b}. \tag{27}$$

A pair of quantities (q_1^*, q_2^*) forms a (Cournot) Nash equilibrium in the second stage game if for each $i, j \in \{1, 2\}$ with $j \neq i$ the quantity q_i^* maximizes the expected profits of firm i when firm j produces the quantity q_j^*. That is, (q_1^*, q_2^*) forms a Nash equilibrium if for each $i, j \in \{1, 2\}$ with $j \neq i$ the quantity q_i^* solves

$$\max_{q_i \geq 0} p^C(q_i, q_j^*)q_i - \frac{c_i(x_i)}{2}q_i^2 - z(x_i). \tag{28}$$

Proposition 2. *Given the R&D levels x_1 and x_2 determined in the first stage of the duopolistic game, the stage-two competition in quantities has a unique Nash equilibrium characterized by $\langle q_1^C(x_1, x_2), q_2^C(x_2, x_1)\rangle$ such that for each $i, j \in \{1, 2\}$ with $j \neq i$,*

$$q_i^C(x_i, x_j) = \frac{1 + bc_j(x_j)}{(2 + bc_i(x_i))(2 + bc_j(x_j)) - 1}. \tag{29}$$

Proof. The first-order necessary condition associated with the maximization problem in (28) is given by

$$-\frac{1}{b}q_i + \frac{a - q_i - q_j^*}{b} - c_i(x_i)q_i = 0. \tag{30}$$

If $(q_1^*, q_2^*) = (q_1^C, q_2^C)$ forms a Nash equilibrium, then for each $i, j \in \{1, 2\}$ with $j \neq i$ the quantity $q_i = q_i^C$ must satisfy the above first-order condition when $q_j^* = q_j^C$, implying

$$q_i^C = \frac{a - q_j^C}{2 + bc_i(x_i)}. \tag{31}$$

Changing the role of i and j in (31), we can also get

$$q_j^C = \frac{a - q_i^C}{2 + bc_j(x_j)}. \tag{32}$$

Then, solving (31) and (32) together, we can obtain $q_i^C(x_1, x_2)$ as in (29). To check the second-order sufficiency condition, we differentiate the left-hand side of (30) with respect to q_i to obtain $-(2/b) - c_i(x_i) < 0$ for all $q_i \geq 0$. So, the quantity $q_i^C(x_i, x_j)$ solves the problem in (28), implying that the strategies $q_1^C(x_1, x_2)$ and $q_2^C(x_2, x_1)$ form a Nash equilibrium in the second-stage game. $\square$.

Define $p^C(x_i, x_j) \equiv p^C(q_i^C(x_i, x_j), q_j^C(x_j, x_i))$ using (27) and (29) and also define $Q^C(x_1, x_2) \equiv q_1^C(x_1, x_2) + q_2^C(x_2, x_1)$. Perfectly anticipating the equilibrium quantities that would be chosen in the second stage of the duopolistic game, firm i can calculate in the first stage its profits $\pi_i^C(x_i, x_j)$, at each possible investment pair (x_i, x_j) where $j \neq i$, as follows:

$$\pi_i^C(x_i, x_j) \quad = \quad p^C(x_i, x_j)\, q_i^C(x_i, x_j) - \frac{c_i(x_i)}{2} q_i^C(x_i, x_j)^2 - z(x_i) \tag{33}$$

A pair of R&D investment strategies (x_1^C, x_2^C) forms a Nash equilibrium if for each $i, j \in \{1, 2\}$ with $j \neq i$, x_i^C maximizes the expected profits of firm i when the R&D level of firm j is x_j^C. That is, x_i^C solves

$$\max_{x_i \geq 0} \quad \pi_i^C(x_i, x_j^C). \tag{34}$$

Given an equilibrium (x_1^C, x_2^C), involving the solution to (34) for each firm, it follows that the strategy profile $\langle (x_1^C, x_2^C), (q_1^C(x_1^C, x_2^C), q_2^C(x_2^C, x_1^C)) \rangle$ constitutes a subgame-perfect Nash equilibrium of the two-stage game played by the duopolists. At this equilibrium, the profits of firm i become

$$\pi_i^C(x_i^C, x_j^C) = p^C(x_i^C, x_j^C) q_i^C(x_i^C, x_j^C) - \frac{c_i(x_i^C)}{2} q_i^C(x_i^C, x_j^C)^2 - \frac{\delta}{2}(x_i^C)^2, \tag{35}$$

whereas the consumer surplus becomes

$$CS^C(x_1^C, x_2^C) = \frac{Q^C(x_1^C, x_2^C)^2}{2b}. \tag{36}$$

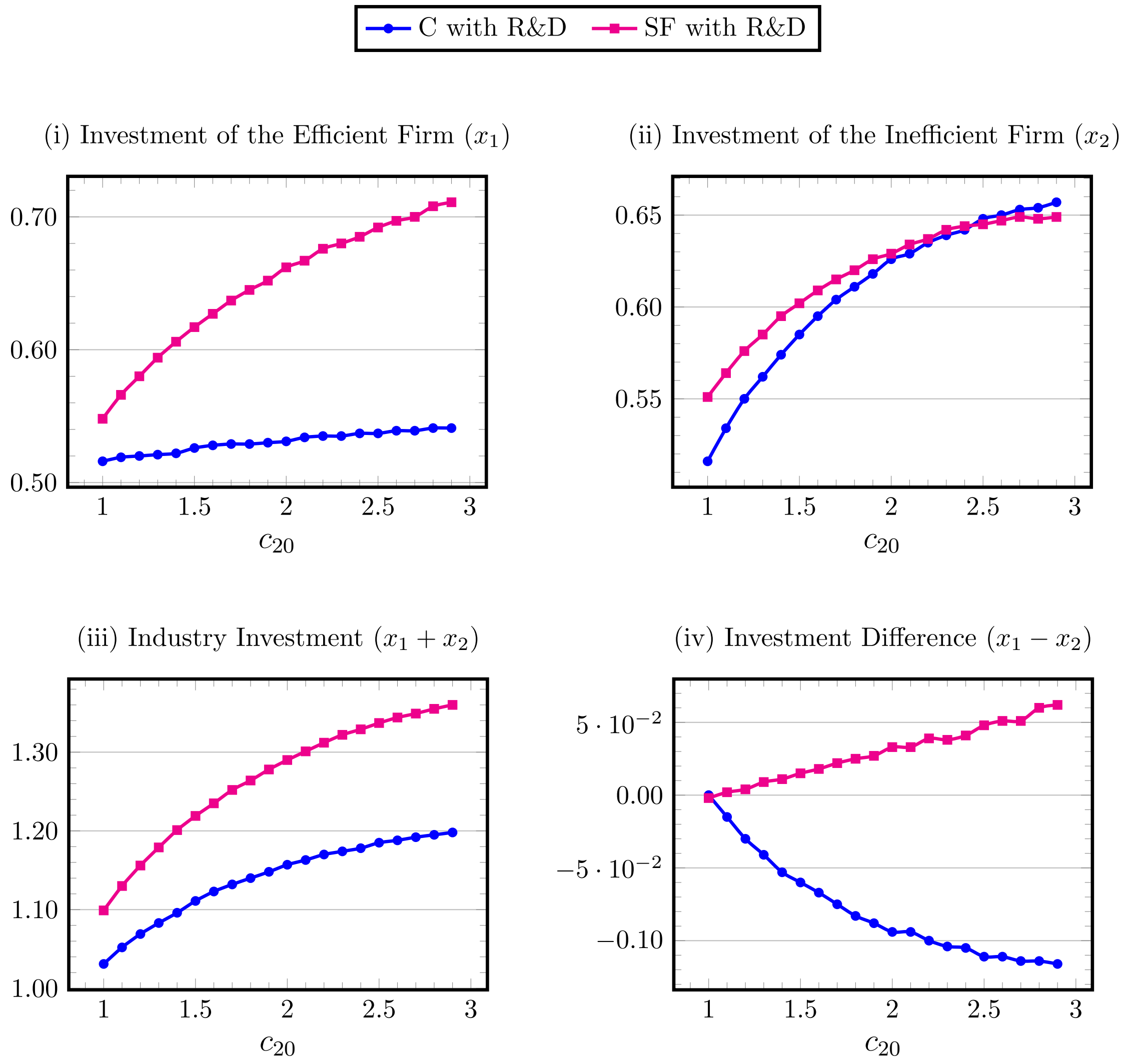
3.3 The Output and Welfare Effects of R&D Investment

Due to the functional complexity of the optimization programs in (23) and (34), we cannot analytically calculate the subgame-perfect Nash equilibria of the two-stage game played by the duopolists. However, we will be able to calculate these equilibria numerically with the help of a computer, using the programming package Gauss Version 3.2.34 (Aptech Systems, 1998). The source code and the simulated data are available from the author upon request.

For our computations, we set $a = 3$, $b = 1$, and $c_{1,0} = 1$, while we vary the parameter $c_{2,0}$ from 1.0 to 2.9 with increments 0.1 and the parameter d from 0.1 to 9.6 with increments 0.5. At each parameter set, we compute the Nash equilibrium in R&D investments with a grid search technique. Basically, given a competition type $t \in \{SF, C\}$ that we have considered in Sections 3.1 and 3.2, we change both $exp(-x_i)$ and $exp(-x_j)$ from 0.005 to 0.995 with increments of 0.005, and calculate all possible $\pi_i^t(x_i, x_j)$ and $\pi_j^t(x_i, x_j)$ values using equation (22) under the supply function competition in the output market and using equation (33) under the Cournot competition. Given these calculations, we pick a pair (x_i^t, x_j^t) of R&D investments to be a Nash equilibrium for the competition type t if $\pi_i^t(x_i^t, x_j^t) \geq \pi_i^t(x_i, x_j^t)$ for all x_i such that $exp(-x_i) \in \{0.05, 0.010, \ldots, 0.995\}$ and $\pi_j^t(x_j^t, x_i^t) \geq \pi_j^t(x_j, x_i^t)$ for all x_j such that $exp(-x_j) \in \{0.05, 0.010, \ldots, 0.995\}$. If there exist multiple Nash equilibria, we pick the Nash equilibrium (x_i^t, x_j^t) with the highest $x_i^t + x_j^t$ value.

In Figures 1-3 below, we compare several outcomes obtained under the competitions considered in Sections 3.1 and 3.2. Note that all graphs in all three figures plot at each simulated value of $c_{2,0}$ the average value of a relevant model outcome, corresponding to the 20 distinct simulation values of d between 0.1 and 9.6.

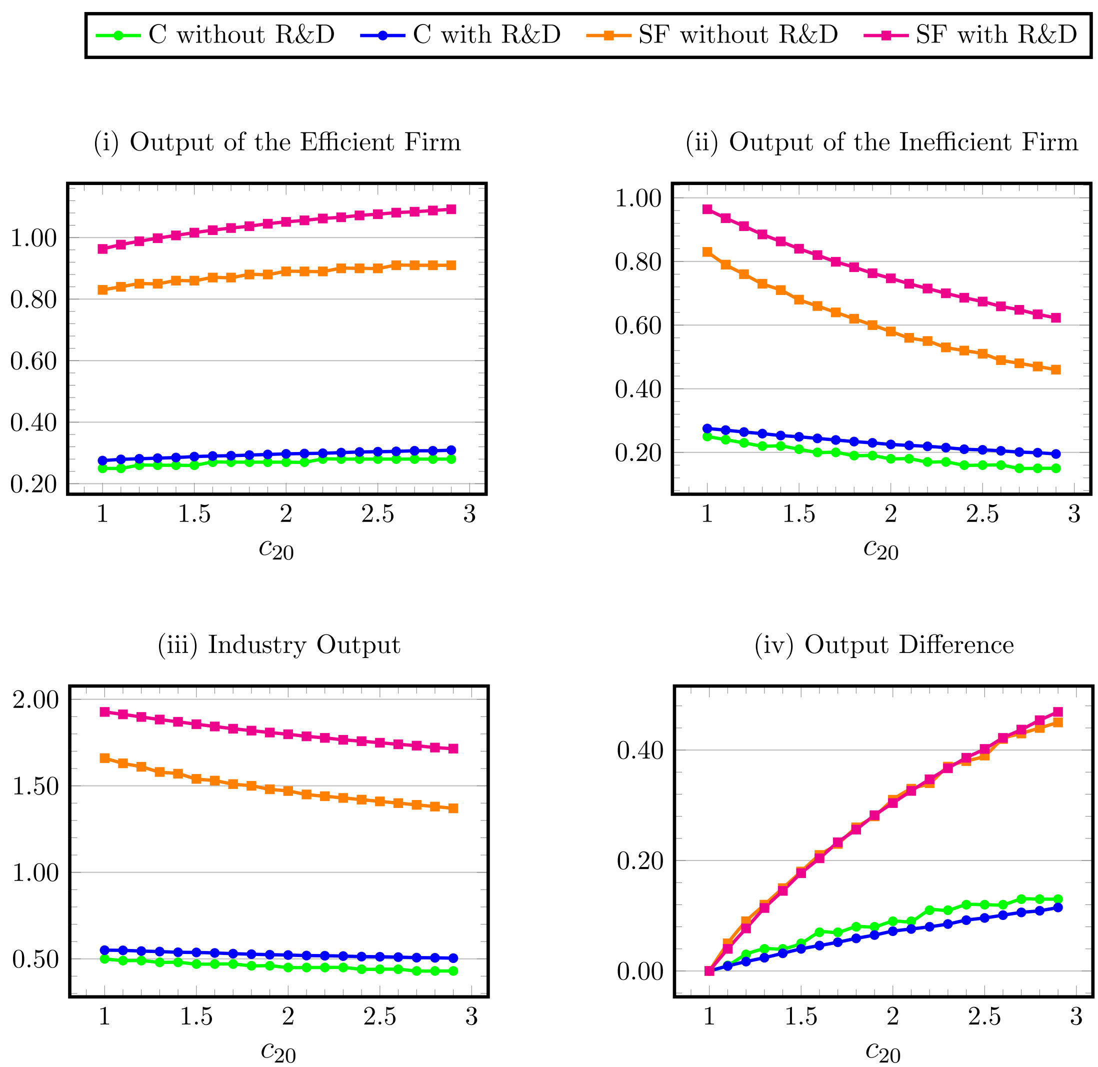
Figure 1. Investments Under the Two Forms of Competitions (C & SF)



In Figure 1, panels (i) and (ii) show that the R&D investment of the efficient firm under the supply function competition is much higher than under the Cournot competition at all levels of cost asymmetry. On the other hand, for the inefficient firm the R&D investment can be slightly higher (lower) under the supply function competition if and only if the cost asymmetry is small to medium (high). Although the R&D level for the whole industry is always significantly higher also under the supply function competition as shown in panel (iii), the firm level differences behave entirely differently under the two types of competitions. As illustrated by panel (iv), the R&D investment of the efficient firm is always higher than that of the inefficient firm under the supply function competition while the opposite becomes true under the Cournot competition.

In Figure 2, we plot the equilibrium outputs both in the presence and absence of R&D. Note that an equilibrium with no R&D can arise in our model when the firms have no access to the R&D technology in equation (2) or when R&D is infinitely costly, i.e. $\delta = \infty$ in equation (3). The first three panels of Figure 2 show that the outputs of both firms as well as the industry output are higher when investment in R&D is present than when it is not. However, the positive effect of R&D seems to be much more significant under the supply function competition than under the Cournot competition.

Figure 2. Comparisons of Outputs Under the Two Forms of Competitions (C & SF)

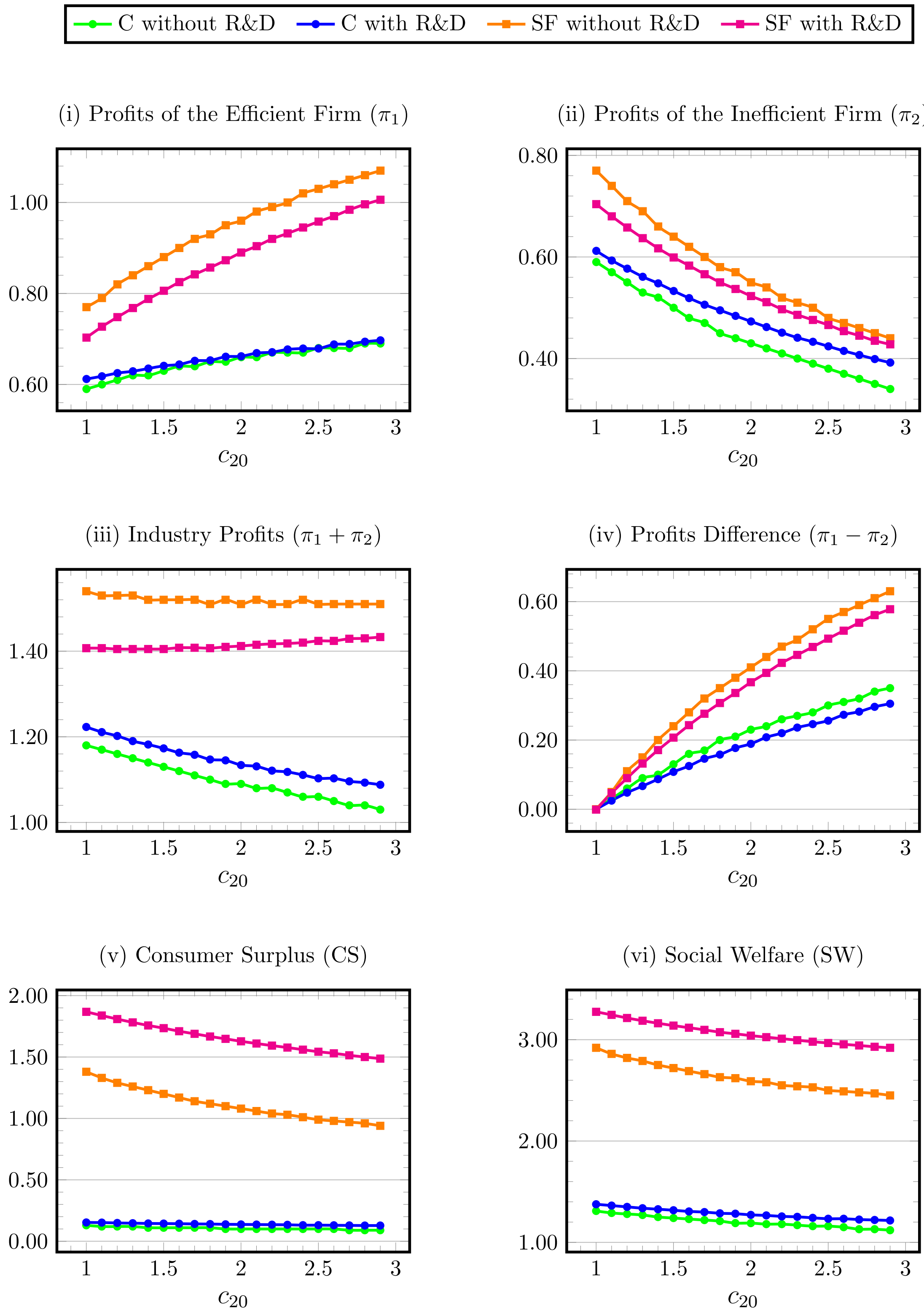


In panels (i) and (ii) of Figure 2 we also observe that the effect of cost asymmetry on output is different for the two firms. For both types of competitions, this effect is positive for the efficient firm and negative (and much larger) for the inefficient firm, irrespective of the presence of R&D possibility. In fact, the said negative effect on the output of the inefficient firm is so large that the industry output is always decreasing in the level of cost asymmetry, as we observe in panel (iii). In addition, we observe in the first three panels that the effect of cost asymmetry becomes always more pronounced when the firms compete in supply functions. Finally, panel (iv) shows that the efficient firm always produces more than the inefficient firm under both types of competitions irrespective of whether the two firms are able to engage in R&D or not. Moreover, the difference between the firms' outputs is always higher under the supply function competition than under the Cournot competition, while this difference is not affected by the possibility of R&D investment much.

Next, in Figure 3 we plot the equilibrium welfares of producers, consumers, and the society as a whole. Panels (i), (ii), and (iii) illustrate the effects of R&D on the profits of the duopolists and the industry as a whole. While this effect is found to be always positive under the Cournot competition, it is always negative under the supply function competition. This latter negative effect is caused by the aggressive investment in R&D, especially by the efficient firm, observed under the equilibrium of the supply function competition (Figure 1), raising the industry output, and consequently reducing the product price, to a harmful level for both firms. Moreover, as expected, an increase in the cost asymmetry has a positive effect on the welfare of the efficient firm and a negative effect on the welfare of the inefficient firm under both types of competitions, irrespective of the presence or absence of R&D. However, which of these opposite effects becomes dominant on the total industry profits is more involving. As illustrated in panel (iii) of Figure 3, when the firms engage in the Cournot competition in the output market, the industry profits are decreasing at all levels of cost asymmetry irrespective of the possibility of R&D investment. On the other hand, when the firms compete in supply functions in the output market, the industry profits are always slightly decreasing with respect to the cost asymmetry in the absence of R&D and always slightly increasing in the presence of R&D. We also observe in panel (iv) that the firm that has an initial cost advantage in production can always obtain higher profits irrespective of the type of competition, the level of cost asymmetry, and the possibility of R&D investment.

Finally, panels (v) and (vi) of Figure 3 illustrate that the effect R&D on the consumer surplus and the social welfare are very significant and positive under the supply function competition and very small, yet positive, under the Cournot competition. Moreover, irrespective of the presence or absence of R&D, the welfares of both consumers and the society as a whole are always higher under the supply function competition. We can also observe that the level of cost asymmetry has, in general, negative effects on the consumer surplus and social welfare, especially under the supply function competition.

Figure 3. Comparisons of Welfares Under the Two Forms of Competitions (C & SF)



4 Conclusion

In this paper we have considered a duopolistic model with cost asymmetry to study how process R&D may affect the welfares of producers, consumers, and the society as a whole when both firms compete either in supply functions or in quantities in the output market. To this end, we have constructed a two-stage perfect-information game where the duopolistic firms non-cooperatively choose in the first stage their R&D investments and in the second stage their productions (according to the supply function or quantity competition). Solving the subgame-perfect Nash equilibrium of this game numerically for a wide range of initial cost parameters, we have found that under both types of competitions the outputs of both firms, and resultingly the industry output, are always higher when they both invest in R&D than when neither of them makes any investment.

We have also observed that the output expansion due to the aggressive R&D investment under the supply function competition becomes so large that the negative effect of this expansion on the profits of the firms and the whole industry outweighs a positive effect stemming from the reduction in the unitary marginal costs of the firms due to R&D. Consequently, under the supply function competition with process R&D the duopolistic firms find themselves trapped in a situation like the Prisoners' Dilemma. Even though R&D can be beneficial for any firm when the rival firm has no access to R&D, it becomes destructive under the supply function competition when both firms non-cooperatively engage in R&D. In contrast, competing in R&D before the Cournot competition in the output market becomes always beneficial for both firms, especially for the inefficient firm. On the other hand, regarding the welfares of consumers and the society as a whole, we have found that R&D has always a positive effect under both types of competitions, whereas this effect is incomparably larger under the supply function.

Our simulations have also showed that the supply function competition is always Pareto superior to the Cournot competition at all levels of cost asymmetry, irrespective of the presence or absence of R&D. Besides, the possibility of R&D competition before the supply function competition in the output market may yield huge welfare benefits for consumers at the expense of huge profit losses for the duopolistic firms. This suggests that public authorities acting on behalf of consumers, or the society as a whole, may have strong incentives to subsidize (or facilitate) non-cooperative R&D investments of the duopolistic firms –at any level of cost asymmetry– when they compete in supply functions, like they usually do in electricity markets. Our findings also imply that social gains from such subsidies might be very small when the duopolistic firms compete in quantities.

Finally, future research may fruitfully extend our work to study the welfare effects of process and/or product R&D in an asymmetric duopoly with differentiated products.

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