Munich Personal RePEc Archive

City and Regional Demand for Vaccines Whose Supply Arises from Competition in a Bertrand Duopoly

Batabyal, Amitrajeet and Beladi, Hamid

Rochester Institute of Technology, University of Texas at San Antonio

9 January 2022

Online at https://mpra.ub.uni-muenchen.de/113758/
MPRA Paper No. 113758, posted 14 Jul 2022 04:27 UTC

City and Regional Demand for Vaccines Whose Supply Arises from Competition in a Bertrand Duopoly[1]

by

AMITRAJEET A. BATABYAL[2]

and

HAMID BELADI[3]

1

We thank the Editors of this volume and three anonymous reviewers for their helpful comments on a previous version of this chapter. In addition, Batabyal acknowledges financial support from the Gosnell endowment at RIT. The usual disclaimer applies.

2

Department of Economics, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14623-5604, USA. E-mail: aabgsh@rit.edu

3

Department of Economics, University of Texas at San Antonio, One UTSA Circle, San Antonio, TX 78249-0631, USA. E-mail: Hamid.Beladi@utsa.edu

City and Regional Demand for Vaccines Whose Supply Arises from Competition in a Bertrand Duopoly

Abstract

We study a one-period model of an aggregate economy composed of cities and regions that demand vaccines designed to fight a pandemic such as Covid-19. The supply of vaccines is the outcome of Bertrand competition between two firms A and B. The marginal cost of producing the vaccine for both firms is stochastic and drawn from a uniform distribution. In this setting, we perform three tasks. First, we describe the equilibrium pricing strategies of the two firms and then we compute their mean *ex ante* profits. Second, we permit both firms to conduct risky R&D and then determine the conditions under which only one firm engages in R&D and conditions under which both do. Finally, we introduce a way of mimicking the effect of increased competition and then analyze the impact of this increased competition on the incentives to conduct R&D faced by the two firms.

Keywords: Bertrand Duopoly, City, Innovation, R&D, Region, Vaccine

JEL Codes: L13, O32, R11

1. Introduction

We now know---see Chaplin (2020) and Batabyal and Beladi (2022)---that the cause of the severe acute respiratory syndrome or SARS-like illness that subsequently became known as Covid-19 was a novel coronavirus, in particular, the SARS-CoV-2. On 30 January 2020, Covid-19 was declared by the WHO to be a Public Health Emergency of International Concern (PHEIC). The first case of Covid-19 arising from local person-to-person spread in the United States (U.S.) was confirmed in mid-February 2020. On 11 March 2020, the WHO declared COVID-19 a pandemic.

Since that time, the pandemic---which is still not under complete control---has spread throughout the world. A recent study[4] points out that the Covid-19 pandemic has led to 6.9 million deaths worldwide which is more than *twice* the number that has been officially reported. Focusing just on the U.S., this same study estimates that 905,000 people have died of Covid-19 since the start of the pandemic. As pointed out by Branswell (2021), it is worth emphasizing two points about this 905,000 number. First, it is about 61 percent *higher* than the death estimate of 561,594 provided in early May 2021 by the U.S. Centers for Disease Control.[5] Second, this number also exceeds the estimated number of U.S. deaths in the so-called Spanish flu pandemic in 1918, which was estimated to have killed approximately 675,000 Americans.

Given the significant health, social, and economic impacts of Covid-19, it is perhaps unsurprising to learn that a lot of faith has been placed on fighting this pandemic with a vaccine. As noted by Torreele (2020) and Stiglitz (2021), governments in the U.S., the United Kingdom,

---

[4] Go to http://www.healthdata.org/special-analysis/estimation-excess-mortality-due-covid-19-and-scalars-reported-covid-19-deaths for more details. Accessed on 5 July 2022.

[5] Go to https://www.cdc.gov/nchs/covid19/mortality-overview.htm to learn more about this point. Accessed on 5 July 2022.

China, and Russia have poured large amounts of money into vaccine development. As a result, Katella (2021) rightly notes that the world now has several efficacious vaccines such as the two-shots messenger RNA or mRNA vaccines developed by Pfizer-BioNTech and Moderna and the one-shot vaccine developed by Johnson and Johnson.

There is some research on how market competition between firms affects the development of vaccines.[6] This notwithstanding, to the best of our knowledge, there is virtually *no* theoretical research on how alternate economic conditions such as changes in cost uncertainty and changes in the nature of the strategic competition between firms influence the incentives to conduct research and development (R&D) in the context of vaccine development. Given this lacuna in the extant literature, our objective in this chapter is to study a one-period model of an aggregate economy made up of cities and regions that demand vaccines designed to fight a pandemic such as Covid-19. The supply of the vaccines is the outcome of Bertrand competition between two firms A and B. The marginal cost of producing the vaccine for both firms is *probabilistic* and drawn from a uniform distribution. The model is based in part on the discussion of Schumpeterian economic growth in Acemoglu (2009, pp. 458-496). In this setting, we first show how the *risk* associated with the conduct of R&D affects whether both firms or only one firm ends up conducting R&D in equilibrium. Second, we demonstrate how increased competition influences the incentives to conduct R&D faced by the two firms in our model.

The remainder of this chapter is organized as follows. Section 2 delineates our theoretical framework. Section 3 describes the equilibrium pricing strategies of the two firms and then

6

See Sloan and Hsieh (2007), Fu *et al.* (2012), Gilchrist and Nanni (2013), Kremer *et al.* (2020), and Martonosi *et al*. (2021) for more on this literature.

computes their expected *ex ante* profits. Section 4 permits both firms to undertake risky R&D and then it ascertains the conditions under which only one firm engages in R&D and conditions under which both do. Section 5 introduces a way of mimicking the effect of increased competition and then analyzes the effect of this increased competition on the incentives to conduct R&D faced by the two firms. Finally, section 6 concludes and then discusses three ways in which the research described in this chapter might be extended.

2. The Theoretical Framework

Consider economic activities that take place in a single time period in an aggregate economy that consists of a finite number of cities and regions. A region, in the context of this chapter, is a sub-national geographic entity and hence a city is a particular kind of region. There are two vaccine producing firms denoted by A and B in our aggregate economy and both these firms produce a vaccine that we shall think of as being a homogeneous good. For concreteness, the reader may want to think of the two firms as the Pfizer and BioNTech alliance and Moderna and the good they produce as the mRNA vaccine. Since the mRNA vaccines produced by these two firms work very similarly and have comparable effectiveness levels,[7] they can, for the purpose of our analysis, be thought of as a homogeneous good.[8] The two vaccine producing firms A and B are the two Bertrand duopolists in our model.[9]

At the beginning of the time period under study, firm $A's$ marginal cost of production is given by a draw from the uniform distribution $[0, \hat{c}_A]$ and firm $B's$ marginal cost of production is

---

77

Go to https://share.upmc.com/2021/01/vaccines-moderna-pfizer/ for more details on this point. Accessed on 5 July 2022.

8

Go to https://www.fraserhealth.ca/health-topics-a-to-z/coronavirus/covid-19-vaccine/mrna#.YsT-pnbMKUc for additional details on this point. Accessed on 5 July 2022.

9

In the remainder of this chapter, we shall use the terms "firm" and "duopolist" interchangeably.

given by an independent draw from the uniform distribution $[0, \hat{c}_B]$.[10] Both duopolists first observe their costs and then they set their prices. Total demand for the vaccines produced by the two duopolists is generated by the governments of the various cities and regions that comprise our aggregate economy. This total demand or Q is given by the linear demand function[11]

$$Q = H - P \tag{1}$$

where P is the price and it is understood that the condition $H > 2\max(\hat{c}_A, \hat{c}_B)$ holds.

With this description of the theoretical framework out of the way, we now proceed to first determine the equilibrium pricing strategies of the two firms and then we compute their expected *ex ante* profits.[12]

3. Pricing and Profits

3.1. Pricing

Let us begin our study of the pricing decisions of the two firms by focusing on the firm with the *lower* cost realization. There is no loss of generality in this approach because, in

---

10

The uniform distribution is easy to work with and it is commonly used within many fields in economics to model the stochastic aspects of a variable. This is why we use the uniform distribution in our analysis. See Wanke (2008) for additional details on this point. In addition, we do not use the Weibull distribution because it is analytically more difficult to work with and because the most common applications of the Weibull distribution typically involve the analysis of survival data. See Mudholkar *et al*. (1996) for more details on this point.

11

An analysis of the competition between two firms to produce a vaccine for use against Covid-19 would be meaningless unless we also model the demand for these vaccines explicitly. That is why we have the total demand function that we do in equation (1). In this chapter, we are primarily interested in studying the nature and the properties of the *competition* between two *firms* to produce vaccines. That is why we have *not* imposed additional structure on the total demand function in equation (1). That said, two points are now worth emphasizing. First, clearly governments can and do perform a variety of role in the context of vaccine development. One such role is to purchase the produced vaccines that they then make available to their citizens. This is the role that we model in the present chapter. Other possible roles include granting patents and making advance purchase agreements with the vaccine producing firms. These roles are discussed briefly in sections 4.1 and 6 below. Second, one could easily give an explicit *spatial structure* to this total demand function. Here are two examples to show how one could do this. Suppose the aggregate economy of interest is that of New York state in the United States. New York state is divided into 62 counties. Suppose the demand for vaccines from the ith county, $i = 1, \dots, 62$, at time t is denoted by q_i. Then, aggregating over space, the total demand for vaccines at time t is the sum of the demand in these 62 counties. In this case, we could write the inverse (and spatial) total demand function as $P = H - Q$ where $Q = \sum_{i=1}^{62} q_i$. Continuing with the first example, suppose we wanted to give a probabilistic flavor to the analysis. Then, the average demand per county or $\bar{q} = (\sum_{i=1}^{62} q_i)/62$. In this last case, we could write the inverse (and spatial) total demand function as $P = H - Q$ where $Q = 62\bar{q}$.

12

In what follows, the model solution techniques we employ are similar to those employed by Peters and Simsek (2009, pp. 287-291).

equilibrium, this will be the only firm that produces the vaccine. That said, what we have to next ascertain is whether this lower cost firm will be able to behave like a monopolist and hence charge the monopoly price or whether this firm will be forced to use limit pricing.[13]

To determine the monopoly price, our lower cost firm uses the demand function given in equation (1) and solves the profit maximization problem

$$max_{\{P\}}(H-P)(P-c) \tag{2}$$

where $c > 0$ is the realized marginal cost. Calculus shows that the monopoly price (P^M) is given by the ratio

$$P^M(c) = \frac{H+c}{2}. \tag{3}$$

Note that it makes sense to write the monopoly price P^M as a function of the marginal cost c because this cost realization is observed by our lower cost firm *before* it sets its price.

Recall our understanding that $H > 2\max(\hat{c}_A, \hat{c}_B)$. Also, we know that $c \in [0, \hat{c}_i], i = A, B$. Using these two pieces of information, we infer that

$$P^M(c) \geq P^M(0) = \frac{H}{2} > \max(\hat{c}_A, \hat{c}_B). \tag{4}$$

Equation (4) tells us that the monopoly price will always be (weakly) higher than the competing duopolist's marginal cost. This means that charging the monopoly price *cannot* constitute equilibrium behavior by our lower cost firm because if this firm attempted to charge the monopoly

13 See Acemoglu (2009, p. 419) for a textbook exposition of limit pricing.

price then its rival could undercut this monopoly price by charging $P^M(c) - \varepsilon$ for some small $\varepsilon > 0$, and still make positive profits. This line of reasoning eliminates the possibility of the lower cost duopolist charging the monopoly price and therefore this finding tells us that in equilibrium, the lower cost duopolist *must* limit price.

To determine the limit pricing equilibrium, let us begin by assuming, with no loss of generality, that $c_A < c_B$. Now observe that in order to ensure that it does not make a loss by producing the vaccine, duopolist B must charge c_B in equilibrium. If it charged more than c_B then, because $c_B < P^M(c_A)$, duopolist A will also charge a price higher than c_B. This pricing behavior *cannot* constitute an equilibrium because duopolist B will now want to undercut duopolist $A's$ price.

In this regard, it is worth emphasizing that in our model, the lower cost firm---temporarily assumed to be duopolist A---must capture the total demand for vaccines in the aggregate economy. To see this, suppose that the above point is not the case and hence duopolist A captures only a fraction $\gamma \in (0,1)$ of the total demand for vaccines. Then, by charging $P_A(c_A, c_B) = c_B - \varepsilon$ for some small $\varepsilon > 0$, duopolist A would capture the entire market for vaccines in our aggregate economy. However, since $c_B - \varepsilon < P^M(c_A)$, the revenue function is a decreasing function of ε. This line of reasoning tells us that there is no equilibrium in which $P_A(c_A, c_B) = c_B - \varepsilon < c_B$. In turn, this last finding leads to the conclusion that there is *no* equilibrium in which duopolist A captures only the fraction $\gamma \in (0,1)$ of the total demand for vaccines when both firms in our model charge c_B.

Note that when duopolist A captures the entire market for vaccines by charging c_B, we have an equilibrium because duopolist B makes zero profit independent of its market share. Finally, the governments of the various cities and regions that are the consumers of the vaccines are indifferent about which firm to buy vaccines from because the produced vaccines are homogeneous.[14] We can now conclude this discussion of pricing by pointing out that the equilibrium limit price or $P^L(c_A, c_B)$ is given by

$$P^L(c_A, c_B) = \max(c_A, c_B), \tag{5}$$

and that the lower cost firm captures the entire market for vaccines.[15]

3.2. Profits

We now ascertain the expected profits $E[\pi_i], i = A, B$ obtained by the two firms. In this regard, notice that because we are looking at the *ex ante* expected profits, the expectations we are considering are unconditional and they are taken over the joint distribution of the two costs c_A and c_B. Using the law of iterated expectations---see Ross (1996, p. 21)---we deduce that the *ex ante* profit of duopolist A is given by

$$E[\pi_A] = E_{c_B}\left[E_{c_A}[\pi_A / c_B]\right]. \tag{6}$$

To compute the above expectation, we need to consider the two relevant cases in which either $\hat{c}_A \geq \hat{c}_B$ or $\hat{c}_A < \hat{c}_B$.

Let us focus on the $\hat{c}_A \geq \hat{c}_B$ case first. Using the properties of the uniform distribution---see Ross (2007, pp. 35-36)---and that of the conditional expectation---see Ross (2007, pp. 105-117)---we reason that

14 If we think of the Pfizer and BioNTech alliance as firm A and Moderna as firm B, then we know that in the real world, it has not been the case that either only the Pfizer and BioNTech alliance or only Moderna has captured the total demand for mRNA vaccines. This discrepancy is most likely explained by the twin facts that we have not modeled advance purchase guarantees---see Section 6 below---by governments and that our model is static and hence unable to analyze repeated interactions between the Pfizer and BioNTech alliance, Moderna, and the pertinent governments.

15 We can think of the knife-edge case in which, notionally, the two firms A and B charge the same price for vaccines as one in which the two firms share the market for vaccines equally.

$$E[\pi_A(\hat{c}_A, \hat{c}_B)/\hat{c}_A \geq \hat{c}_B] = \int_0^{\hat{c}_B} \left\{ \int_0^{c_B} \{(c_B - c_A)(H - c_B)\} \frac{1}{\hat{c}_A} dc_A \right\} \frac{1}{\hat{c}_B} dc_B. \quad (7)$$

After several steps of algebra, the right-hand-side (RHS) of equation (7) can be simplified. This simplification gives

$$E[\pi_A(\hat{c}_A, \hat{c}_B)/\hat{c}_A \geq \hat{c}_B] = \frac{H\hat{c}_B^2}{6\hat{c}_A} - \frac{\hat{c}_B^3}{8\hat{\hat{c}}_A}. \quad (8)$$

Next, focusing on the $\hat{c}_A < \hat{c}_B$ case, we get

$$E[\pi_A(\hat{c}_A, \hat{c}_B)/\hat{c}_A < \hat{c}_B] = \int_0^{\hat{c}_A} \left\{ \int_{c_A}^{\hat{c}_B} \{(c_B - c_A)(H - c_B) \frac{1}{\hat{c}_B} dc_B \right\} \frac{1}{\hat{c}_A} dc_A. \quad (9)$$

As in the case of the $\hat{c}_A \geq \hat{c}_B$ case, once again, we can simplify the RHS of equation (9), Doing this, we get

$$E[\pi_A(\hat{c}_A, \hat{c}_B)/\hat{c}_A < \hat{c}_B] = \frac{H\hat{c}_A^2}{6\hat{c}_B} + \frac{H(\hat{c}_B - \hat{c}_A)}{2} + \frac{\hat{c}_A\hat{c}_B}{4} - \frac{\hat{c}_A^3}{24\hat{c}_B} - \frac{\hat{c}_B^2}{3}. \quad (10)$$

Equations (8) and (10) together give us the *ex ante* profit that duopolist A can expect to earn by producing vaccines. Since duopolist $B's$ problem is symmetric to that of duopolist A, we can easily write the analogous *ex ante* profit that duopolist B can expect to earn.[16]

16

In the real world, from the standpoint of 2021, the Pfizer and BioNTech alliance and Moderna were both expected to make significant profits in 2022 from the manufacture and sale of their respective mRNA vaccines. This standpoint is similar to the notion of *ex ante* expected profits that we have been discussing in this section. See Dunleavy (2021) for additional details on this point.

Our next task is to allow both firms to undertake risky R&D and to then determine the conditions under which only one firm engages in R&D and conditions under which both do.

4. Risky R&D

4.1. Firm payoffs

Suppose that the two firms A and B in our aggregate economy begin their competition in the market for vaccines with the cost distribution $[0, \hat{c}]$. In addition, suppose that both firms can conduct R&D with fixed cost $\zeta > 0$.[17] If they do conduct R&D then with probability $\theta > 0$, their cost distribution changes to $[0, \hat{c} - \beta]$ and we assume that $\hat{c} > \beta$. We shall interpret the situation in which the cost distribution changes as one in which a firm is successful in coming up with an *innovation* that reduces the cost of producing a vaccine.

We do not discuss patents explicitly in this chapter but consistent with an observation of Tirole (1988, p. 394), the sort of R&D competition that we are analyzing in this chapter can be thought of as a race for a patent. So, if our focus were to be on patents then we would want to recognize that either firm A or B might want to accelerate its R&D at the cost of incurring additional expenditures. Put differently, if an appropriate regulator in our aggregate economy were to give rise to a rent and here the rent would arise from the monopoly situation created by a patent, then there would be competition for this rent and hence it would be partly dissipated by the additional costs that would be incurred to appropriate it.[18]

Now, the decision to conduct R&D has to be made *before* the two firms realize what the actual cost of producing vaccines is going to be. Therefore, a firm will choose to conduct R&D if

---

17

See Danzon and Pereira (2011) for a discussion of the importance of fixed costs in the context of the development of vaccines.

18

See Lee (2022) for a discussion of the practical pros and cons of granting patents to the two leading producers of mRNA vaccines and Gaviria and Kilic (2021) for a more general discussion of mRNA vaccine patents.

and only if this decision leads to higher *ex ante* profit. What complicates this decision for either firm is that as shown in equations (8) and (10), firm $A's$ *ex ante* profit depends on whether firm B chooses to conduct R&D and vice versa.

To study the equilibrium that arises when either firm makes a decision to conduct R&D, let us first define a firm's expected profit as a function of the outcome of the decision to conduct R&D. To this end, let Π_{00} denote the expected profit to a firm when the decision to conduct R&D leads to failure, i.e., results in no cost reducing innovation, and hence the cost distribution for both firms remains $[0, \hat{c}]$. Let Π_{10} denote the expected profit to a firm when its decision to conduct R&D leads to a cost reducing innovation, this firm's cost distribution changes to $[0, \hat{c} - \beta]$, and hence this firm displaces the other firm and becomes a cost leader. Let Π_{01} be the expected profit to our firm if its competitor's decision to conduct R&D leads to a cost reducing innovation, the competitor's cost distribution changes to $[0, \hat{c} - \beta]$, and hence this competitor displaces the first firm and becomes a cost leader. Finally, let Π_{11} represent the case where the decision to conduct R&D by both firms leads to cost reducing innovations and therefore both face the changed cost distribution $[0, \hat{c} - \beta]$. Some thought tells us that for, say, the ith firm, $i = A, B$, we get

$$\Pi_{00} = E[\pi_i(\hat{c}, \hat{c}/\hat{c}_A \geq \hat{c}_B] = \frac{H\hat{c}}{6} - \frac{\hat{c}^2}{8}, \tag{11}$$

$$\Pi_{10} = E[\pi_i(\hat{c} - \beta, \hat{c}/\hat{c}_A < \hat{c}_B] = \frac{H(\hat{c}-\beta)^2}{6\hat{c}} + \frac{\hat{c}(\hat{c}-\beta)}{4} + \frac{H\beta}{2} - \frac{(\hat{c}-\beta)^3}{24\hat{c}} - \frac{\hat{c}^2}{3}, \tag{12}$$

$$\Pi_{01} = E[\pi_i(\hat{c}, \hat{c} - \beta/\hat{c}_A \geq \hat{c}_B] = \frac{H(\hat{c}-\beta)^2}{6\hat{c}} - \frac{(\hat{c}-\beta)^3}{8\hat{c}}, \tag{13}$$

and

$$\Pi_{11} = E[\pi_i(\hat{c} - \beta, \hat{c} - \beta / \hat{c}_A \geq \hat{c}_B] = \frac{H(\hat{c}-\beta)}{6} - \frac{(\hat{c}-\beta)^2}{8}. \quad (14)$$

The decision by our vaccine producing firms to conduct R&D can be conceptualized as a static game in which each firm has two actions denoted by $a_i, i = A, B$. These actions are "Conduct R&D" denoted by R and "Don't conduct R&D" denoted by D. In symbols, we have $a_i \in \{R, D\}$. The payoffs to the two firms as a function of the two available actions can be expressed as $W_i(a_i, a_j), i \neq j$. In addition, the four specific payoffs written out in full detail are

$$W_i(R, R) = (1-\theta)^2\Pi_{00} + \theta(1-\theta)\Pi_{10} + \theta(1-\theta)\Pi_{01} + \theta^2\Pi_{11} - \zeta, \quad (15)$$

$$W_i(R, D) = (1-\theta)\Pi_{00} + \theta\Pi_{10} - \zeta, \quad (16)$$

$$W_i(D, R) = (1-\theta)\Pi_{00} + \theta\Pi_{01}, \quad (17)$$

and

$$W_i(D, D) = \Pi_{00}. \quad (18)$$

To interpret the above four payoffs, consider, for instance, the payoff $W_i(R, R)$ given by equation (15). The situation in which both firms fail to generate a cost reducing innovation from their decision to conduct R&D occurs with probability $(1-\theta)^2$ and the associated expected profit term is Π_{00}. This explains the first term on the RHS of equation (15). The situation in which only one of the two firms generates a cost reducing innovation with its decision to conduct R&D occurs with probability $\theta(1-\theta)$. The associated expected profit terms are either Π_{10} or Π_{01}. This explains the second and the third terms on the RHS of equation (15). The case where both firms generate a cost reducing innovation occurs with probability θ^2 and the related expected profit term is Π_{11}. This explains the fourth term on the RHS of equation (15). Finally, observe that a firm has to pay the fixed cost of ζ whenever it decides to conduct R&D and this explains the fifth and last term on the RHS of equation (15). Similar interpretations can be given to the three remaining payoffs given in equations (16) through (18).

4.2. Nash equilibria

Our task now is to determine the Nash equilibria of the static game that we have been describing thus far. To this end, let us first focus on the two possible *symmetric* equilibria. In these equilibria, both firms take similar actions as far as the decision to conduct or not conduct R&D is concerned.

The first symmetric Nash equilibrium is where both firms conduct R&D. This happens when

$$W_i(R,R) \geq W_i(D,R) \Leftrightarrow \theta\{\theta(\Pi_{11} - \Pi_{01}) + (1-\theta)(\Pi_{10} - \Pi_{00})\} \geq \zeta. \quad (19)$$

Let us interpret what the condition in (19) is telling us in three steps. First, by conducting R&D, a firm generates a cost reducing innovation with probability θ. This is the θ that appears outside the expression in the curly brackets in (19). Second, conditional on generating a cost reducing innovation, the marginal benefit to the firm is $(\Pi_{11} - \Pi_{01})$ if its rival also generates a cost reducing innovation, which happens with probability θ, and the marginal benefit is $(\Pi_{10} - \Pi_{00})$ if its rival fails to generate a cost reducing innovation, which happens with probability $(1-\theta)$. This explains the presence of the expression inside the curly brackets in (19). Finally, putting the preceding two points together, as long as the expected marginal benefit from conducting R&D exceeds the fixed cost ζ, it is a Nash equilibrium for each firm to conduct R&D.

The second symmetric Nash equilibrium occurs when both firms decide *not* to conduct R&D. In this case, we have

$$W_i(D,D) \geq W_i(R,D) \Leftrightarrow \theta(\Pi_{10} - \Pi_{00}) \leq \zeta. \quad (20)$$

The condition in (20) tells us that the expected benefit to a firm from conducting R&D or $\theta(\Pi_{10} - \Pi_{00})$ does not exceed the fixed cost ζ incurred when conducting this R&D. When this condition holds we have another possible Nash equilibrium.

In addition to the above two symmetric Nash equilibria, in principle, it is possible for there to exist an *asymmetric* Nash equilibrium in which only one firm conducts R&D. In this instance, we need two conditions to hold simultaneously. These two conditions are

$$W_i(R, D) \geq W_i(D, D) \; and \; W_i(D, R) \geq W_i(R, R). \tag{21}$$

In words, the two conditions in (21) tell us that we need one firm to want to conduct R&D when the other firm does not *and* we also need the other firm to not want to conduct R&D when the first firm wants to conduct R&D. As in the case of the two possible symmetric Nash equilibria discussed above, it is possible to use the various expected profit expressions in equations (11) through (14) and rewrite the two conditions in (21). Doing this, we get

$$\theta(\Pi_{10} - \Pi_{00}) \geq \zeta \geq \theta\{\theta(\Pi_{11} - \Pi_{01}) + (1 - \theta)(\Pi_{10} - \Pi_{00})\}. \tag{22}$$

To summarize the discussion in this section, we have seen that there is a symmetric Nash equilibrium---see (19)---in which both firms conduct R&D and, in addition, there is also an asymmetric Nash equilibrium---see (22)---in which only one of the two vaccine producing firms in our aggregate economy conducts R&D. Our final task in this chapter is to present a way of mimicking the effect of increased competition and to then analyze the impact of this increased competition on the incentives faced by the two firms to conduct R&D and generate potentially cost reducing innovations.

5. Increased Competition

5.1. A decrease in $\hat{c}$

Recall from section 4 that the cost distribution faced by the duopolists in our model is given by $[0, \hat{c}]$. Now suppose that the upper endpoint of this distribution or $\hat{c}$ declines. We shall interpret this decline in $\hat{c}$ as being equivalent to an *increase* in the competition between the duopolists under study. To examine the impact of this increased competition on the innovation incentives faced by the duopolists, let us differentiate equation (11) with respect to $\hat{c}$. This gives us

$$\frac{\partial \Pi_{00}}{\partial \hat{c}} = \frac{H}{6} - \frac{\hat{c}}{4} > 0. \tag{23}$$

The sign of the derivative in equation (23) follows from our understanding---see section 2---that $H > 2\max(\hat{c}_A, \hat{c}_B) = 2\hat{c}$. Given this sign result, we emphasize that a decline in $\hat{c}$ can be interpreted as an *increase* in competition because this decline *reduces* a firm's pre-cost reducing innovation profits.[19]

5.2. Firm incentives

Now, to analyze the impact of this increase in competition on the incentives to conduct R&D and to generate possibly cost reducing innovations faced by the duopolists, let us define the two functions $\psi_1(\hat{c}, \beta, H)$ and $\psi_2(\hat{c}, \beta, H)$ where

$$\psi_1(\hat{c}, \beta, H) = \Pi_{10} - \Pi_{00} = \frac{\beta}{24\hat{c}}\{\beta^2 + 4H\beta + \hat{c}(4H - 3\beta) - 3\hat{c}^2\} \tag{24}$$

[19] Our focus on studying the effects of increased competition in the market for vaccines is consistent with the viewpoint of the United Nations Conference on Trade and Development (UNCTAD). Go to https://unctad.org/news/defending-competition-markets-during-covid-19 for more details on this point. Accessed on 6 July 2022.

and

$$\psi_2(\hat{c},\beta,H) = \Pi_{11} - \Pi_{01} = \frac{\beta}{24\hat{c}}\{4H(\hat{c}-\beta) - 3(\hat{c}-\beta)^2\}. \tag{25}$$

In words, the two functions given by equations (24) and (25) capture the benefit from generating a cost reducing innovation. Specifically, $\psi_1(\hat{c},\beta,H)$ describes the *increase* in expected profit obtained by a firm when it generates a cost reducing innovation and its rival does *not* conduct R&D. Similarly, $\psi_2(\hat{c},\beta,H)$ describes the *increase* in expected profit obtained by a firm when it generates a cost reducing innovation and its rival *does* conduct R&D.

Differentiating the functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$ with respect to $\hat{c}$, it is straightforward to verify that

$$\frac{\partial\psi_1(\hat{c},\beta,H)}{\partial\hat{c}} = -\frac{\beta}{24}\left\{\frac{\beta^2+4\beta H+3\hat{c}^2}{\hat{c}^2}\right\} < 0 \tag{26}$$

and

$$\frac{\partial\psi_2(\hat{c},\beta,H)}{\partial\hat{c}} = \frac{\beta}{24}\left\{\frac{3\beta^2+4\beta H-3\hat{c}^2}{\hat{c}^2}\right\} \gtrless 0. \tag{27}$$

Even though the sign of the partial derivative in equation (27) is, in general, indeterminate, if β is large enough then we can reasonably expect the sign of this derivative to be *positive*. To keep the subsequent mathematical analysis tractable, in what follows, we shall assume that this is, in fact, the case.

To comprehend why the signs of the derivatives in equations (26) and (27) are as they are, note the following line of reasoning. First, with regard to equation (26), if competition between the two vaccine producing firms is intense (this happens when $\hat{c}$ is small) then the benefit to a firm from generating a cost reducing innovation is *high* $\{\psi_1(\cdot)$ is high$\}$ when this firm's rival does *not* conduct R&D. This explains the negative sign of the derivative in equation (26). Second and in contrast, the incentive to a firm to conduct R&D and generate a cost reducing innovation is *low* $\{\psi_2(\cdot)$ is low$\}$ if this firm's rival is also *conducting* R&D. This last finding arises because more intense competition between the two firms *reduces* the value of, so to speak, "getting ahead" when one's rival is "already ahead."

Using the descriptions of the two functions $\psi_1(\cdot)$ and $\psi_2(\cdot)$, we can rewrite the three inequality conditions given in (19), (20), and (22). This gives us

$$\theta\{\theta\psi_2(\hat{c},\beta,H) + (1-\theta)\psi_1(\hat{c},\beta,H)\} \geq \zeta, \tag{28}$$

$$\theta\psi_1(\hat{c},\beta,H) \leq \zeta, \tag{29}$$

and

$$\theta\psi_1(\hat{c},\beta,H) \geq \zeta \geq \theta\{\theta\psi_2(\hat{c},\beta,H) + (1-\theta)\psi_1(\hat{c},\beta,H)\}. \tag{30}$$

Recall that (28) refers to the symmetric Nash equilibrium in which both vaccine producing firms conduct R&D. Similarly, (29) concerns the symmetric Nash equilibrium in which neither of the two firms conduct R&D. Finally, (30) refers to the asymmetric Nash equilibrium in which only one firm conducts R&D.

Inspecting (28) through (30) carefully, it is clear then when there is increased competition in the market for vaccines, i.e., when $\hat{c}$ declines, the value of the function $\psi_1(\hat{c},\beta,H)$ rises and hence the condition given in (29) is *less likely* to be satisfied. Therefore, in an environment with increased competition, the benefit to a firm from conducting R&D and stochastically generating a cost reducing innovation is high. This means that a symmetric Nash equilibrium in which neither firm conducts R&D is *unlikely* to occur.

If the probability of generating a cost reducing innovation or θ is high enough then, differentiating the condition given in (28) with respect to $\hat{c}$, we get

$$\frac{\partial\{\theta\psi_2(\hat{c},\beta,H+(1-\theta)\psi_1(\hat{c},\beta,H)\}}{\partial\hat{c}} > 0. \tag{31}$$

The inequality in (31) tells us that with increased competition or with a decrease in $\hat{c}$, the symmetric Nash equilibrium in which both firms conduct R&D is also *unlikely*. To see why this is the case a little differently, observe that as the probability θ of generating a cost reducing innovation approaches one, it becomes increasingly more likely that a decision to conduct R&D by the two firms will lead to a cost reducing innovation for both of them. That said, if competition between the two firms in the market for vaccines is intense then even the profit after having generated a cost reducing innovation is likely to be low compared to the fixed cost ζ of conducting R&D. This line of reasoning tells us that the condition given in (28) is unlikely to be satisfied and therefore a symmetric Nash equilibrium in which both vaccine producing firms conduct R&D is also *unlikely* to exist.

Having eliminated the conditions specified in (28) and (29), it follows that the only remaining case is the condition given in (30). We claim that this condition is most likely to be satisfied in an environment with increased competition. To see why, note the following three-part line of reasoning. First, in the absence of R&D, the rents obtained by the two firms are low because rising competition lowers expected profits for both firms. Second, to reduce competition, one firm will want to generate a cost reducing innovation but only if the other firm decides to not pursue the same strategy---of wanting to generate a cost reducing innovation---simultaneously. Finally, the preceding two points together lead to the conclusion that when competition between the two firms in the market for vaccines is intense, the asymmetric Nash equilibrium in which only *one* firm conducts R&D and hence potentially generates a cost reducing innovation is the *most likely* scenario.

We have pointed out in our analysis thus far in this section that certain kinds of equilibria are less likely to occur in the static game between the Bertrand duopolists under study. That said, it should be noted that the effect of increased competition on aggregate expenditures on R&D in general is *ambiguous*. To see this, consider the following two cases.

In the first case, suppose that in the *status quo*, neither firm conducts R&D. In this case, when competition policy reduces $\hat{c}$ over time, the condition in (29) for the symmetric Nash equilibrium in which neither firm conducts R&D will be violated. When this happens, at least one firm will conduct R&D. Clearly, in this case, increased competition between the duopolists will lead to an *increase* in aggregate expenditure on R&D. In the second case, suppose that in the *status quo*, both firms conduct R&D. In this case, increased competition between the two firms *may* move our aggregate economy to an asymmetric equilibrium in which only one firm conducts R&D. Obviously, in this second case, increased competition between the duopolists leads to a *diminution* in aggregate expenditures on R&D. This completes our discussion of the demand for vaccines by cities and regions when their supply is the outcome of competition in a Bertrand duopoly

6. Conclusions

In this chapter, we analyzed a one-period model of an aggregate economy composed of cities and regions that demanded vaccines designed to fight a pandemic such as Covid-19. The supply of the vaccines was the outcome of Bertrand competition between two firms A and B. The marginal cost of producing the vaccine for both firms was stochastic and drawn from a uniform distribution. In this setting, we performed three tasks. First, we delineated the equilibrium pricing strategies of the two firms and then we computed their expected *ex ante* profits. Second, we allowed both firms to conduct risky R&D and then ascertained the conditions under which only one firm conducted R&D and conditions under which both did. Finally, we proposed a way of mimicking the effect of increased competition and then studied the impact of this increased competition on the incentives to conduct R&D faced by the two firms.

The analysis in this chapter can be extended in a number of different directions. Here are two potential extensions. First, it would be interesting to model the Bertrand competition between the duopolists in the market for vaccines when one or more city and regional governments are able to commit to an advance agreement to purchase a certain quantity of the produced vaccines. Second, it would also be informative to study a scenario in which one or more city and regional governments attempt to increase competition in the market for vaccines by offering incentives such as subsidies to firms willing to enter this market. Such actions will involve an analysis not of a duopoly but, more generally, an oligopoly with $n > 2$ potential firms. Finally, one could also study scenarios in which the cost of producing a vaccine is quadratic, firms compete to produce a vaccine in order to obtain a patent and thereby secure monopoly rights over the produced vaccine, and the pertinent consumers are cities that are---like in the Hotelling (1929) model---uniformly distributed along a straight line with length one. Studies that analyze these aspects of the underlying problem will provide additional insights into the nature of competition policy, the behavior of firms with market power, and the ultimate development of vaccines.

References

Acemoglu, D. 2009. *Introduction to Modern Economic Growth*. Princeton University Press, Princeton, NJ.

Batabyal, A.A., and Beladi, H. 2022. Health interventions in a poor region and resilience in the presence of a pandemic. Forthcoming, *Applied Spatial Analysis and Policy*.

Branswell, H. 2021. New analysis finds global Covid death toll is double official estimates, *STAT*, May 6. https://www.statnews.com/2021/05/06/new-analysis-finds-global-covid-death-toll-is-double-official-estimates. Accessed on 5 July 2022.

Chaplin, S. 2020. COVID-19: A brief history and treatments in development, *Prescriber*, May, 23-28.

Danzon, P.M., and Pereira, N.S. 2011. Vaccine supply: Effects of Regulation and Competition, *International Journal of the Economics of Business*, 18, 239-271.

Dunleavy, K. 2021. Pfizer, Moderna will rake in a combined $93 billion next year on COVID-19 vaccine sales: Report, https://www.fiercepharma.com/pharma/pfizer-moderna-will-rake-a-combined-93-billion-next-year-covid-19-sales-says-analytics-group. Accessed on 5 July 2022.

Fu, Q., Lu, J., and Lu, Y. 2012. Incentivizing R&D: Prize or subsidies? *International Journal of Industrial Organization*, 30, 67-79.

Gaviria, M., and Kilic, B. 2021. A network analysis of COVID-19 mRNA vaccine patents, *Nature Biotechnology*, 39, 546-548.

Gilchrist, S.A.N., and Nanni, A. 2013. Lessons learned in shaping vaccine markets in low-income countries: A review of vaccine market segment supported by the GAVI alliance, *Health Policy and Planning*, 28, 838-846.

Hotelling, H. 1929. Stability in competition, *Economic Journal*, 39, 41-57.

Katella, K. 2021. Comparing the COVID-19 Vaccines: How Are They Different? *Yale Medicine*, August 13. https://www.yalemedicine.org/news/covid-19-vaccine-comparison. Accessed on 5 July 2022.

Kremer, M., Levin, J.D., and Snyder, C.M. 2020. Designing advance market commitments for new vaccines, *National Bureau of Economic Research Working Paper 28168*, Cambridge, MA.

Lee, N. 2022. Experts seriously doubt whether patent waivers on Covid-19 vaccines will ever come to be, https://www.cnbc.com/2022/01/22/why-moderna-pfizer-and-the-nih-debate-who-owns-the-covid-vaccine.html. Accessed 5 July 2022.

Martonosi, S.E., Behzad, B., and Cummings, K. 2021. Pricing the COVID-19 vaccine: A mathematical approach, *Omega*, 103, 102451.

Mudholkar, G.S., Srivastava, D.K., and Kollia, G.D. 1996. A generalization of the Weibull distribution with application to the analysis of survival data, *Journal of the American Statistical Association*, 91, 1575-1583.

Peters, M., and A. Simsek. 2009. *Solutions Manual for Introduction to Modern Economic Growth*. Princeton University Press, Princeton, NJ.

Ross, S.M. 1996. *Stochastic Processes*, 2nd edition. Wiley, New York, NY.

Ross, S.M. 2007. *Introduction to Probability Models*, 9th edition. Academic Press, Burlington, MA.

Sloan, F.A., and Hsieh, C. Eds. 2007. *Pharmaceutical Innovation*. Cambridge University Press, Cambridge, UK.

Stiglitz, J.E. 2021. Globalization in the aftermath of the pandemic and Trump, *Journal of Policy Modeling*, 43, 794-804.

Tirole, J. 1988. *The Theory of Industrial Organization*. MIT Press, Cambridge, MA.

Torreele, E. 2020. Business-as-usual will not deliver the COVID-19 vaccines we need, *Development*, 63, 191-199.

Wanke, P. 2008. The uniform distribution as a first practical approach to new product inventory management, *International Journal of Production Economics*, 114, 811-819.