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Stefano Quarta, University of Salento, Lecce, Italy
Skerdilajda Zanaj, Université du Luxembourg

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For editorial correspondence, please contact: crea@uni.lu
University of Luxembourg
Faculty of Law, Economics and Finance
162A, avenue de la Faïencerie
L-1511 Luxembourg

UNIVERSITÉ DU LUXEMBOURG

Health and Pollution in a Vertically Differentiated Duopoly*

Stefano Quarta†and Skerdilajda Zanaj‡

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Abstract

In this paper, we analyze a vertically differentiated mixed duopoly in medical care services. Pollution is the source of illness. The government has a dual role. It decides how much to invest to reduce the pollution level and it may participate in the health market running a public hospital. We find that the presence of the public provider increases the average quality of the service in the market and it reduces the rate of mortality. Furthermore, when the public hospital offers services with the highest quality, then this has positive spillovers on the quality offered by the private provider. Despite these positive welfare improving features, the mixed duopoly in medical care goes along with a highest level of pollution. In the presence of an increasing concern about the relationship between pollution and health, understanding the role of public intervention appears crucial.

Key words: pollution, health, public provider, mixed duopoly.

JEL codes: L13, H42, H44, I11

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†Corresponding Author: Facoltà di Economia, University of Salento, Centro Ecotekne Pal. C - S.P. 6, Lecce - Monteroni - LECCE (Italy). Email: stefano.quarta@unisalento.it S. Quarta was supported by a scholarship of University of Salento during his stay at the University of Luxembourg in April-July 2017.

‡CREA, University of Luxembourg. Address: 162A, avenue de la Faiencerie, L-1511, Luxembourg. Tel: (+352) 4666 44 6464; Fax (+352) 46 66 44 6341 email: skerdilajda.zanaj@uni.lu

1 Introduction

Outdoor pollution is a major cause of death and diseases worldwide. The health effects range from increased hospital admissions and emergency room visits, to increased risk of premature death. An estimated 4.2 million premature deaths globally are linked to air pollution (WHO, 2018). Furthermore, annual expenditures range from US$240 billion to US$630 billion or approximately three to nine percent of global spending on health care in 2013 in USA (Preker *et al*, 2016). Pollution is known as a causal factor for certain chronic diseases, especially cancer, cardiovascular and respiratory diseases, that have durable detrimental impacts in terms of illness and disability. According to Briggs (2003) about 8-9% of the total disease burden may be attributed to pollution in developed countries.

In this paper, we examine the relation between pollution and health when the medical care market is served by a private and a public provider. Each provider chooses endogenously the quality of its service. Pollution is the main cause of the disease. Our aim is to analyze how the presence of a public hospital affects the choice of the government between the public investment to reduce pollution and quality of the service in the public hospital. Quality is a key concern for patients and policy-makers in health care markets. In this paper, quality of the hospital embodies the quality of the service, the quality of the physicians, the use of modern technologies (OECD 2015), short waiting time, etc.

This issue has attracted not much attention in previous theoretical literature in environmental economics that has especially focused on the market effects of the taxation on greenhouse emission and its best formulation as for instance the carbon tax. However, each year many countries estimate the economic impact of pollution in terms of direct expenditure for treatments, loss of productivity or other economic losses. In this paper, we consider these losses and the alternative pollution reduction cost in terms of a welfare loss.

To capture some features of the medical care market as well as to focus on pollution as a factor that negatively affects health, we use a standard vertical differentiated mixed duopoly model.

The government determines the amount of public investment that fights pollution and it also participates in running a public hospital. Many countries used to organize their health care sector as a public service, but more recently many have introduced competition with the rationale of increasing quality. The resulting structure of the market consists of public and private providers that we represent using a mixed duopoly.[1] The choice of a duopoly well suits the empirical evidence that medical markets are very concentrated (Gaynor and Town, 2011). OECD projections show that *public* spending on health and long-term care is on course to reach almost 9% of GDP in 2030 and as much as 14% of GDP by 2060 (OECD 2015).

The relationship between quality of medical care and hospital ownership (public vs private) is mixed. For instance, Bjorvatn (2018) documents a shorter waiting time and shorter length of stay in private hospitals. However, Tynkkynen and Vrangbæk (2018) through "a scoping review of hospital services in Europe" show how many studies state a higher efficiency and even a higher quality of public hospitals with respect to private ones. Shaikh et al (2018) investigate the relationship between social class and waiting time at health facilities finding that social status is positively related to higher waiting time only if visiting a private facility; whereas in governmental medical care the relationship between waiting time and social status is not significant. In view of this diverging empirical results, we analyze the choice of quality between the private and public hospital as endogenous. We consider a duopoly market under different scenarios: a private duopoly with two profit maximizer providers and then a mixed duopoly with a public welfare maximizer and a private profit maximizer. The two providers choose the price and the qualities of their service in a

[1] There are many different ways to access to the medical care services. In some countries like Italy, UK, Sweden and Canada, the access to the medical care service is covered by the general taxation and the consumer has to pay, at most, a low ticket. In many other countries (Germany, Luxembourg, Japan among others) there is a mandatory public insurance that covers a percentage of the cost or the amount exceeding an annual deductible (like in Netherlands). In Singapore the public insurance is optional, whereas in many american countries (USA or Latin Americans) the State ensures the access to medical services to old or poor agents (or, sometimes, it is guaranteed the access to basic services to the whole population), then private insurances cover the remaining services. China is the country with the most interesting evolution in the management of the medical care service. Between 1949 and 1984, the communist government created a full public system in order to face the very high mortality in the country. Starting from the 1984 there has been the transition to a free market configuration that created many problems, because hospitals remained public, the financing was greatly reduced and a great share of population had no possibility to access to medical services. In the 2003 and 2008 a series of reforms tried to ensure basic services to the whole population, leading to a medical care market similar to the common public system worldwide.

two stage sequential game: in the first stage they choose simultaneously the quality level, whereas in the second, providers set prices.

From the seminal paper of Gabszewicz and Thisse (1979), the literature has given prominence to mixed vertically differentiated models, describing the effects of the presence of a public firm. Several aspects has been investigated: the existence of a first-mover advantage both in the price and the quality stage (Delbono *et al* 1996), the characterization of quality choice without an ex ante assumption about the market coverage (Wauthy, 1996), the effect on the timing for entry (which results to always be simultaneous) if there is a public firm (Liu and Lu, 2014); the effect on welfare efficiency (Grilo, 1994, Lutz and Pezzino, 2014); the effect on different quality-cost configuration (Motta, 1993); or the effect of a partial privatization (Ishibashi and Kaneko, 2008). In the present paper, for the first time, this well-known setting is introduced in the health markets in presence of pollution issues.

The main results of the paper are as follows. We find that in the private duopoly configuration, there is the lowest average quality provided. Crucially, in the private duopoly there is the highest number of agents that remain uncured due to the high price of the medical care service. This makes the private configuration the scenario with the lowest welfare level. Nonetheless, in a pure private market configuration in medical care with the government only investing to reduce pollution, there is the lowest level of pollution. Last, the mixed duopoly configuration with the public hospital offering the highest quality service is characterized by the lowest mortality rate.

Relevant related literature encompasses research on the effect of pollution on health as well as studies documenting competition and quality in medical care. Ebenstein *et al* (2015) show that air pollution clearly affects the cardiorespiratory mortality rate in China, one of the most polluted and emerging economy in the world. Other works like Calderón-Garcidueñas *et al* (2014), Harris *et al* (2016) or Brockmeyer and D'Angiulli (2016) show how pollution can cause a neuroinflammation which leads to neural, behavioral and cognitive change.

There exist a relatively vast *empirical* literature about the effect of competition in quality choices of medical care providers. Propper *et al* (2008) testifies improvements in quality of health care due to the introduction of competition elements. Gravelle *et al* (2014) empirically study whether hospitals compete in quality, finding that hospital's quality is positively associated with the quality of its rivals. This result suggests that any policy which increases the quality in one hospital will have positive effects on the level of quality in other providers. Tay (2003) uses very detailed individual data to firstly characterize the demand function in health markets and then to emphasize the importance of quality differentiation of hospital in a spatially differentiated market. It appears that geographic market concentration is an inappropriate measure of hospital competitiveness. Gutacker *et al* (2016) analyses the relationship between hospital quality competition and the quality aspects that determine the choice of hospital. Using UK data, authors show that it is the health gain dimension of the quality that explains the demand for medical care. In this paper, using a well-established theoretical model in industrial organisation, we bring together the governmental decision on how much to invest in environmental actions that reduce pollution's negative effects on health as well as competition in quality and prices in health markets.

The paper is organized as follows. In Section 2 assumptions of the model are stated. In Section 3 and 4 private and mixed duopoly are analyzed, respectively. In Section 5 the optimal pollution level is analyzed. In Section 6, rather than focusing on the level of welfare in each market configuration, we use the mortality rate as the comparison criteria between scenarios. Some conclusions are underscored in Section 7.

2 The Model

Agents and Pollution. Consider a country with a heterogeneous population whose numerosity is normalized to 1. The heterogeneity is due to a different willingness to pay s_i, uniformly distributed over $[0, 1]$, for the purchase of the medical care service.

Agents living in this country may get a disease with probability q. We assume that the disease is transversal and it shows randomly among the population regardless of the agents' willingness to pay. This implies that the distribution of the willingness to pay is the same among sick agents and the whole population.[2] Hence, a share q of every willingness to pay gets sick as illustrated in the picture below:

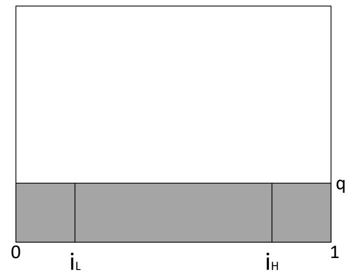


Figure 1: The total population is normalized to one, whereas the share of the population that obtains the disease (in dark grey) is equal to q.

Medical care service. The medical care service can have two different quality levels $\theta_L, \theta_H \in [0;1]$ (with $\theta_L < \theta_H$). The high and the low quality demand functions are, respectively, q_H and q_L:

$$q_H = q(1 - i_H) = q(1 - \frac{p_H - p_L}{\theta_H - \theta_L}) \text{ and } q_L = q(i_H - i_L) = q\frac{\theta_L p_H - \theta_H p_L}{\theta_L(\theta_H - \theta_L)} \tag{1}$$

and they are determined by the two indifferent consumers i_H and i_L:

$$i_H = \frac{p_H - p_L}{\theta_H - \theta_L} \text{ and } i_L = \frac{p_L}{\theta_L}.$$

The unserved market, i.e. the portion of the market composed by agents who want to buy the service but have a willingness to pay too low even for the low quality service is denoted by u.

Therefore the total number of sick agents q is the sum of the number of agents served by the two providers plus the unserved market u:

$$q = q_H + q_L + u.$$

Agents utility. Agents have a utility function that depends on the state of health and the state of illness. The first state gives a utility level denoted by s_i. Each sick agent has a level of

[2] By this assumption, we are excluding the case in which agents who get sick are predominantly "rich" or "poor" (in terms of willingness to pay). For instance, think of the pollution produced by a coal power plant which may pollute for kilometres, an area large enough to reach poor and rich agents.

utility $\theta_j s_i$ net of the price for the required medical care service.[3] Hence, the utility function of the generic agent i is:

$$U_i(s_i, q, p_j, \theta_j) = \begin{cases} s_i & \text{if healthy} \\ \theta_j s_i - p_j & \text{if sick and hospitalized} \\ 0 & \text{if sick and not hospitalized} \end{cases}, \quad j = H, L; \quad i \in (0,1)\,.$$

As expected, healthy agents have the highest utility,[4]sick agents that are not hospitalized have a null utility (because they have to face the disease alone), and finally, sick and hospitalized agents have a utility which depends on the quality and the price of the purchased service.

Hospitals. On the supply side, there are two providers. Firstly, we consider the private duopoly (with two profit maximizer firms) and then, the mixed duopoly scenario with a public welfare maximizer and a private profit maximizer. The two providers choose the price and the quality of the service in a two-stage sequential game: in the first stage, they choose the quality level, whereas in the second, they set prices.

The two firms have the same technology and face a quadratic, quality dependent, cost function:

$$C(\theta_j) = k\theta_j^2 q_j, \quad k > 0. \tag{2}$$

Pollution. The government has the possibility to reduce pollution by sustaining a cost that depends on the severity of the pollution and on the endemic capability to withstand the disease α, $\alpha < q$:[5]

$$P(q) = (q - \alpha)^2\,. \tag{3}$$

Since both the number of sick agents and the pollution reduction cost are usually directly related to the level of pollution, we assume that q is both the share of sick agents and the cost that the government has to pay to reduce the pollution. The parameter α reduces the pollution cost,

[3] Although worldwide there are many different medical care service systems, most of the time based on a public or private insurance market, we want to abstract from this wide range of systems by assuming a standard market dynamics based on the payment of a market price.

[4] This assumption does not affect the price and quality stages but it becomes relevant in the pre-stage, where the government optimizes the pollution level.

[5] We can also see α as the easiness to maintain a low level of pollution (due to the strong immune system of the population).

because a high natural capability to withstand the disease reduces the relevance of pollution's effects. For example, if a population is resistant to a specific pollutant (for a natural condition), that population may withstand a higher level of that specific pollutant with respect to other populations. Finally, using the quadratic form allows to consider that it is (marginally) easier to clean a slightly polluted site rather than a site polluted for a long period.

The government chooses the level of pollution/sickness q before the market competition of the two firms (for this reason we call it a pre-stage). In this pre-stage, it maximizes the welfare taking into account the pollution reduction cost P and the extra-welfare due to healthy agents. The government chooses the optimal level of q that maximizes this augmented welfare function. This second element is usually not take into account in a standard vertical differentiation model.

3 Private duopoly

In this section, we analyze the case of two private profit maximizing providers. In this scenario, the role of the government consists only of the regulation of the pollution level. This ultimately means that the governments selects the share q of agents that will get ill. We solve the model backwards.

The objective function of the private firm is to maximize profits π_j :

$$\underset{p_j,\theta_j}{Max}\pi_j = p_j q_j - k\theta_j^2 q_j. \tag{4}$$

Under symmetry, there are two possible specular equilibria. In each one there is a firm that chooses high quality (H) and a firm that chooses low quality (L). From (1), (2) and (4), the resulting profit functions are:

$$\begin{aligned} \pi_H(p_H, p_L, \theta_H, \theta_L) &= (p_H - k\theta_H^2)(1 - \tfrac{p_H - p_L}{\theta_H - \theta_L})q \\ \pi_L(p_H, p_L, \theta_H, \theta_L) &= (p_L - k\theta_L^2)\tfrac{\theta_L p_H - \theta_H p_L}{\theta_L(\theta_H - \theta_L)} q. \end{aligned} \tag{5}$$

Solving the price stage, and being the concavity conditions satisfied, prices as functions of the quality obtains as:

$$
\begin{aligned}
p_H(\theta_H, \theta_L) &= \frac{\theta_H \left(2\theta_H \left(1 + k\theta_H\right) + \left(k\theta_L - 2\right)\theta_L\right)}{4\theta_H - \theta_L} \\
p_L(\theta_H, \theta_L) &= \frac{\theta_L \left(\theta_H - \theta_L + k\theta_H \left(\theta_H + 2k\theta_L\right)\right)}{4\theta_H - \theta_L}
\end{aligned}
$$

and the profit functions with respect to qualities become:

$$
\begin{aligned}
\pi_H(\theta_H, \theta_L) &= q\theta_H^2 \frac{\theta_H - \theta_L}{\left(\theta_L - 4\theta_H\right)^2} \left(2 - 2k\theta_H - k\theta_L\right)^2 \\
\pi_L(\theta_H, \theta_L) &= q\theta_H\theta_L \frac{\theta_H - \theta_L}{\left(\theta_L - 4\theta_H\right)^2} \left(k\theta_L - k\theta_H - 1\right)^2.
\end{aligned}
$$

Solving the quality stage, and being the concavity conditions satisfied, we find the following equilibrium qualities and equilibrium prices:

$$
\begin{aligned}
\theta_H^* &= \frac{0.40972}{k} \text{ and } p_H^* = \frac{0.22662}{k} \\
\theta_L^* &= \frac{0.19936}{k} \text{ and } p_L^* = \frac{7.5006 \times 10^{-2}}{k}.
\end{aligned}
$$

The profits for each firm as function of the number of sick agents is:

$$
\pi_H^* = \frac{1.6407 \times 10^{-2}}{k} q \text{ and } \pi_L^* = \frac{1.2147 \times 10^{-2}}{k} q.
$$

The corresponding market shares are for the high quality service q_H^*, for the low quality service q_L^*, and the uncovered market u, i.e. the share of sick agents that are not hospitalized are:

$$
q_H^* = 0.27926q; \;\; q_L^* = 0.3445q; \;\; u = 0.37624q.
$$

Finally, the average reservation prices for high and low quality consumers are $\check{s}^* = 0.54848$ and $\hat{s}^* = 0.86037$, respectively. In this Scenario, the average quality $\bar{\theta}^P$ weighted for the market shares is $\bar{\theta}^P = \frac{0.183}{k} q$.

4 Mixed duopoly

Now we study the setting in which one of the two firms has a public owner and maximizes the welfare instead of its profit. In this situation, *it is not* indifferent which firm offers the low quality service and which one offers the high quality one. Thus, we consider two different scenarios. In **Scenario A**, the public firm offers the low quality service and the private firm offers the high quality one. In **Scenario B,** the opposite occurs.

We will distinguish the public and the private firm for their objective function, W for the public hospital and π for the private one, respectively. The low/high quality choice is indicated by the subscript L and H, respectively.

4.1 Scenario A: the public firm offers the low quality service

The private firm has the same objective function as in the private duopoly case, namely:

$$\underset{p_H,\theta_H}{Max}\pi_H(p_H,p_L,\theta_H,\theta_L)=(p_H-k\theta_H^2)\left(1-\frac{p_H-p_L}{\theta_H-\theta_L}\right)q$$

whereas the objective function of the public firm is:

$$\begin{aligned}\underset{p_L,\theta_L}{Max}W_L(p_H,p_L,\theta_H,\theta_L) &= (\theta_L\check{s}-p_L)\,q_L+(\theta_H\hat{s}-p_H)\,q_H \\ &\quad+\left(p_L-k\theta_L^2\right)q_L+\left(p_H-k\theta_H^2\right)q_H. \end{aligned} \tag{6}$$

In the latter equation, the first two addends are the consumer surpluses for those who buy from the public and the private firm respectively; whereas $(p_L-k\theta_L)\,q_L$ is the public firm's profit, and finally $(p_H-k\theta_H)\,q_H$ is the private firm's profit.

Since the willingness to pay is uniformly distributed in the unit interval, $\check{s}$ and $\hat{s}$ are the average willingness to pay of agents who buy the low quality and those who buy the high quality service, respectively.[6]

[6] In the pre-stage analysis we will include, in the formulation of welfare, the share $(1-q)$ of individuals that have no diseases and have the average willingness to pay $\tilde{s}$, which is the mean of all agents (due to the initial assumption that they are randomly extract from the whole distribution). In this stage this additional addend is irrelevant, because it has no relevant variables for the price and the quality stage.

The above mentioned average willingness to pay are:

$$\begin{aligned} \tilde{s} &= \frac{1}{2} \\ \check{s} &= \frac{i_H + i_L}{2} = \frac{\theta_L p_H + p_L(\theta_H - 2\theta_L)}{2\theta_L(\theta_H - \theta_L)} \\ \hat{s} &= \frac{1 + i_H}{2} = \frac{\theta_H - \theta_L + p_H - p_L}{2(\theta_H - \theta_L)}. \end{aligned} \tag{7}$$

Therefore, using (1) and (2), (6) we can rewrite W_L. Proceeding as usual by backward induction, we solve the price stage and it turns out the following equilibrium prices (in terms of qualities) are:

$$\begin{aligned} p_H(\theta_H, \theta_L) &= \frac{\theta_H \left(\theta_H - \theta_L + k\left(\theta_H^2 + \theta_L^2 - \theta_H\theta_L\right)\right)}{2\theta_H - \theta_L} \\ p_L(\theta_H, \theta_L) &= \frac{\theta_L \left(\theta_H - \theta_L + k\theta_H(2\theta_L - \theta_H)\right)}{2\theta_H - \theta_L}. \end{aligned}$$

Using these expressions for prices, we rewrite the objective function that each firm maximizes to select the optimal level of quality to provide. Being the concavity conditions satisfied, the equilibrium qualities are:

$$\theta_H^* = \frac{0.37995}{k} \text{ and } \theta_L^* = \frac{0.25882}{k}.$$

Then, the optimal prices obtains as:

$$p_H^* = \frac{0.17754}{k} \text{ and } p_L^* = \frac{8.9589 \times 10^{-2}}{k}.$$

Therefore, the optimal level of welfare and the profit of the private firm are:

$$\pi_H^* = \frac{9.0878 \times 10^{-3}}{k} q \text{ and } W_L^* = \frac{7.7545 \times 10^{-2}}{k} q.$$

The corresponding market shares for the Scenario A, for the high quality service, for the low quality service, and the uncovered market, are:

$$q_H^* = 0.27391q;\ q_L^* = 0.37994q;\ u = 0.34615q.$$

Finally, the average willingness to pay for high and low quality consumers are $\check{s}^* = 0.53612$ and $\hat{s}^* = 0.86304$, respectively. In this Scenario, the average quality (weighted for the market shares) is $\bar{\theta}^{Ga} = \frac{0.202}{k}q$.

Comparing the outcome of Scenario A with the outcome in the private duopoly we find **that**,

Proposition 1 *In a vertically differentiated mixed duopoly, if the private firm is the high quality service provider and the public firm is the low quality service provider, the average quality provided is higher than the corresponding one under private duopoly.*

4.2 Scenario B: the public firm offers the high quality service

In this alternative Scenario, the private firm offers the low quality **service**, whereas the public one provides the high quality service. The objective functions are the following:

$$\begin{array}{r}
\underset{p_L,\theta_L}{Max}\pi_L(p_H,p_L,\theta_H,\theta_L) = (p_L - k\theta_L^2)\frac{\theta_L p_H - \theta_H p_L}{\theta_L(\theta_H - \theta_L)}q \\
\underset{p_H,\theta_H}{Max}W_H(p_H,p_L,\theta_H,\theta_L) = q_L\left(\theta_L\check{s} - p_L\right) + q_H\left(\theta_H\hat{s} - p_H\right) \\
+\left(p_L - k\theta_L^2\right)q_L + \left(p_H - k\theta_H^2\right)q_H.
\end{array}$$

Then we have the same formulation for average willingness to pay levels $\check{s}$, $\hat{s}$ and $\tilde{s}$ as for the Scenario A (see 7).

By solving the price stage, the optimal prices as functions of the level of qualities are:

$$p_H\left(\theta_L,\theta_H\right) = \frac{k\theta_H\left(2\theta_H^2 - \theta_L^2\right)}{2\theta_H - \theta_L} \text{ and } p_L\left(\theta_L,\theta_H\right) = \frac{k\theta_L\left(\theta_H^2 - \theta_L^2 + \theta_H\theta_L\right)}{2\theta_H - \theta_L}.$$

Given these expressions for prices, solving the FOC system, and being the concavity conditions satisfied, the equilibrium qualities are:

$$\theta_H^* = \frac{0.389\,83}{k} \text{ and } \theta_L^* = \frac{0.259\,89}{k}$$

yielding the following optimal prices

$$p_H^* = \frac{0.17730}{k} \text{ and } p_L^* = \frac{9.2871\times 10^{-2}}{k}.$$

Finally, we obtain the optimal level of welfare and profit as:

$$W_H^* = \frac{7.7916 \times 10^{-2}}{k} q \text{ and } \pi_L^* = \frac{7.405\,2 \times 10^{-3}}{k} q.$$

For the Scenario B, the corresponding market shares for the high quality service, for the low quality service, and the uncovered market are

$$q_H^* = 0.35025q; \; q_L^* = 0.29241q; \; u = 0.35734q.$$

The average willingness to pay for high and low quality consumers are $\check{s}^* = 0.50355$ and $\hat{s}^* = 0.82488$, respectively. In this Scenario, the average quality, weighted for the market shares), is $\bar{\theta}^{Gb} = \frac{0.213}{k} q$.

Proposition 2 *In a vertically differentiated mixed duopoly, if the public firm is the high quality service provider, the average quality is the highest as compared with Scenario A and the private duopoly. Both qualities are the highest than in any other scenario.*

4.3 Quality choice

Since $W_H^* > W_L^*$ and $\pi_H^* > \pi_L^*$ $\forall q, k$, we can conclude that there is a clear advantage to choose the high quality for both firms. As in Delbono *et al* (1996), there are two subgame perfect Nash equilibria. Furthermore, in each of the two mixed scenarios the private profit is lower than any profit in the pure private duopoly, whereas the welfare is higher. The result is that the private firm prefers to compete in a private duopoly (offering the high quality service) and the public firm prefers to compete in the Scenario B of the mixed duopoly (offering the high quality service).

Since there is not a unique equilibrium, we compute the optimal pollution level for each case, leaving the comparative analysis for the end.

5 Pre-stage: Optimal choice of pollution level

In this section, we examine the pre-stage of the game in the three different market configurations. In this pre-stage, the government chooses the optimal pollution level.

We will indicate the private duopoly with the apex P and the mixed duopoly with the apex Ga for the Scenario A, and the apex Gb for the Scenario B. The government maximizes the welfare with respect to q. We argue that the pollution reducing investment, and thus the percentage of the number of agents that have the disease, is a costly process for the government. As we have assumed in the model setting section with (3), the cost function $P(q)$ is convex with respect to q: the higher the number of potential sick agents, the higher the cost to be sustained (assuming that a high number of sick agents is implied by a high level of pollution). In other words, the higher the level of pollution, the higher the cost to reduce the pollution. To compute the optimal level, the government maximizes the augmented welfare, which considers the number of healthy agents $\frac{1}{2}(1-q^r)$ and subtracts the pollution reduction cost $(q^r-\alpha)^2$, $r=P,Ga,Gb$. Recall that the parameter α is the specific endurance of the population to the pollution and it allows us to adapt the pollution reduction cost function to the specificity of each population.

In the private duopoly model, given the equilibrium values of the price-quality optimization, the government maximizes the following augmented welfare function with respect to q^P:

$$\breve{W}^P = \frac{1}{2}(1-q^P) + \frac{7.5541\times 10^{-2}}{k}q^P - \left(q^P-\alpha\right)^2$$

and the resulting optimal pollution level in the pure private duopoly model is:

$$q^P = -\frac{2.7411\times 10^{-7}}{k}\left(9.1206\times 10^5 k - 3.648\,2\times 10^6 k\alpha - 1.378\times 10^5\right).$$

In the **Scenario A** of the mixed duopoly model, the government maximizes the following augmented welfare function with respect to q^{Ga}:

$$\breve{W}_L^{Ga} = \frac{1}{2}(1-q^{Ga}) + \frac{7.7545\times 10^{-2}}{k}q^{Ga} - \left(q^{Ga}-\alpha\right)^2$$

that leads to the optimal pollution level in the mixed duopoly model (with the public firm which offers the low quality service):

$$q^{Ga} = -\frac{2.5\times10^{-6}}{k}\left(10^5k - 4.0\times10^5k\alpha - 15509\right).$$

Finally, in Scenario B of the mixed duopoly and given the equilibrium values of the price-quality optimization, the government maximizes the following augmented welfare function with respect to q^{Gb}:

$$\breve{W}_H^{Gb} = \frac{1}{2}(1-q^{Gb}) + \frac{7.7916\times10^{-2}}{k}q^{Gb} - \left(q^{Gb}-\alpha\right)^2$$

and the resulting optimal pollution level in the mixed duopoly model (with the public firm which offers the high quality service) is:

$$q^{Gb} = \frac{2.0\times10^{-6}}{k}\left(-1.25\times10^5k + 5.0\times10^5k\alpha + 19479\right).$$

We are now in condition to establish the size of the uncovered market, the level of welfare at the optimal level of pollution in the two possible outcomes of the strategic interaction Scenario A and Scenario B. By Propositions 1, 2 and 3, we observe that in the private duopoly configuration, there is the highest *high quality services* and the lowest *low quality services* provided, leading to the widest spread between two qualities. Furthermore, in the private duopoly there is the highest unserved share market. Hence, despite the lowest low quality, the corresponding price is not so low and there are more agents with a willingness to pay lower than the required price.

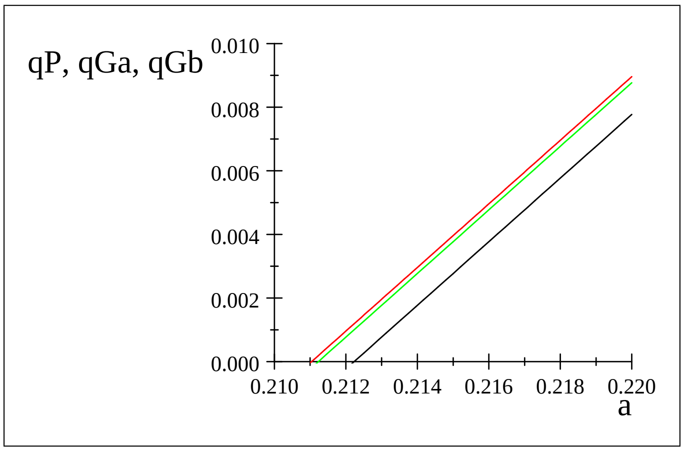
Proposition 3 *In the private duopoly model there is the highest unserved share of the market.*

In the private duopoly model the welfare is lower than in the two mixed cases. This is the well known result, in the literature, that the high quality good gives a premium both in terms of profit or welfare. For this reason both the private and the public firm have the incentive to choose high quality. Therefore, as far as the welfare is concerned, the mixed duopoly with the public firm which offers the high quality service is the market configuration which leads to the highest welfare.

Proposition 4 *In a private duopoly there is the lowest welfare.*

Finally, by comparing the optimal pollution level in the three analyzed cases, it holds $q^P < q^{Ga} < q^{Gb}$ $\forall\alpha$ (see Figure 2). Hence,

Proposition 5 *In a private duopoly configuration in medical care and a government that intervenes only to invest in pollution reduction, there is the lowest level of pollution.*



Optimal pollution level (or number of sick agents) with respect to parameter α in the public (Scenario A: green line; Scenario B: red line) and private (black line) duopoly.

To conclude, the presence of the public firm in the medical market improves quality and, as an indirect consequence, makes less convenient the reduction of the amount of pollution (for a given parameter α). In other words, the chance to directly take care of sick agents reduces the convenience on spending on a lower pollution level. Hence, in a vertically differentiated medical care service model where the government has the possibility to choose the level of pollution, the optimal solution in terms of welfare is a mixed duopoly with the public firm that offers the high quality service. This is nevertheless not the most environmentally friendly market configuration.

6 An alternative evaluation

Health markets are, by definition, a very sensible topic because the traded "good" in the market is the health of agents. The quality of the service affects the probability of successfully treating the disease, hence, the quality affects not only the consumers satisfaction but also the mortality rate. The mortality rate cannot be seen as a measure of quality of service *per se*, but as an outcome defined by the quality of the service (Gaynor and Town, 2011). Hospitals are thus not choosing mortality rates, but rather a quality of service level that has an impact on mortality. Accordingly, welfare is not the only measure to consider to evaluate market configuration. It could be relevant to investigate the number of agents that would perish due to the disease, given the choice of quality and prices.

Under the assumption that quality affects the risk to perish, then the *unserved agents* face the highest risk. For this reason, in the following, we assume a mortality function that depends negatively on the quality of the service but it is positively affected by a parameter of quality effectiveness $\delta \in \mathbb{R}$. The effectiveness considers how much quality really affects the mortality rate. For example, there are some rare diseases for which it is possible to use only palliative care. In those cases, the quality does not matter so much and its effectiveness is low.

The resulting mortality rate D^r is multiplied by the respective number of agents who buy the specific service:

$$D^r = \sum_{j=L,H,u} \left[q_j^r \left(1 - \theta_j^r\right)^{\delta} \right],$$

where j indicates the purchased quality, r indicates the market configuration. The unserved agents receive a quality θ^u that is equalized to 0.

For simplicity set $k = \alpha = 1$. It is easy to verify that the number of perished agents D^P in the private duopoly is:

$$D^P = q_H^P \left(1 - \left(\theta_H^P\right)\right)^{\delta} + q_L^P \left(1 - \left(\theta_L^P\right)\right)^{\delta} + u^P = 0.21999 \times 0.59028^{\delta} + 0.27139 \times 0.80064^{\delta} + 0.29639.$$

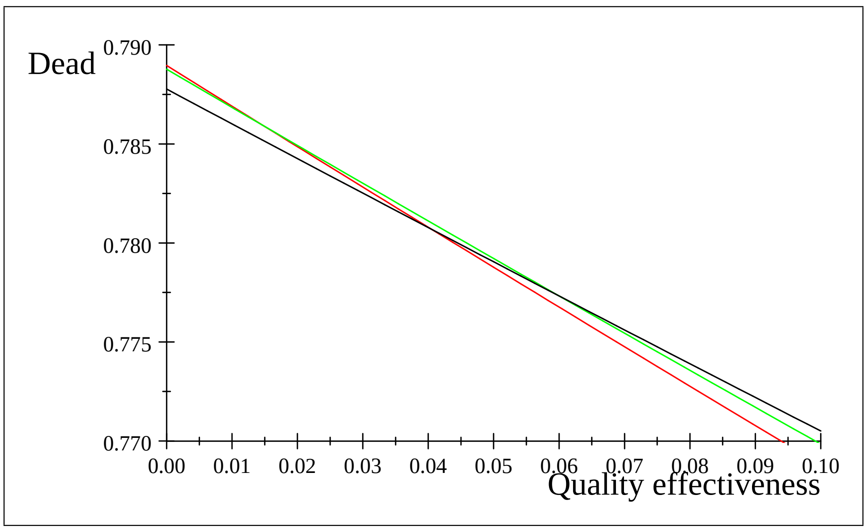
The number of perished agents D^{Ga} in the mixed duopoly (Scenario A) is:

$$D^{Ga} = q_H^{Ga} \left(1 - \left(\theta_H^{Ga}\right)\right)^{\delta} + q_L^{Ga} \left(1 - \left(\theta_L^{Ga}\right)\right)^{\delta} + u^{Ga} = 0.21605 \times 0.62005^{\delta} + 0.29969 \times 0.74118^{\delta} + 0.27303.$$

Finally, the number of perished agents D^{Gb} in the mixed duopoly (Scenario B) is:

$$D^{Gb} = q_H^{Gb}\left(1-\left(\theta_H^{Gb}\right)\right)^{\delta} + q_L^{Gb}\left(1-\left(\theta_L^{Gb}\right)\right)^{\delta} + u^{Gb} = 0.27633 \times 0.61017^{\delta} + 0.2307 \times 0.74011^{\delta} + 0.28193.$$

In Figure 3, we represent the number of perished agents in each market configuration. The graph shows that the mortality rate is the lowest in private duopoly if $\delta < 0.04054$. By contrast, if $\delta > 0.04054$, then the mortality rate is the lowest in Scenario B.



Number of perished agents as a function of the quality effectiveness rate δ in the public (Scenario A: green line; Scenario B: red line) and private (black line) duopoly.

The result yields from the higher pollution level allowed in the mixed model - which leads to a higher number of sick agents - and the higher average quality (even considering the lower unserved market share) - which reduces the probability to perish. Hence, the mortality rate is lower in the private model only if the quality effectiveness is very low, because in that case the number of sick agents would be more relevant than the average quality offered.

Finally, by considering that in the advanced economies the medical care service quality strongly matters, we can conclude that:

Conclusion 6 *In a vertically differentiated model of medical care where the government has the possibility to choose the level of pollution, the mixed duopoly (with the public firm offering the high* *quality service) is the preferred market configuration not only in terms of welfare but also in terms of the number of agents that may perish.*

7 Conclusion

In this paper we have analyzed a duopoly model in the medical care service market, by considering environmental pollution as the sole reason for illness. In the model, the government has the possibility to reduce the pollution level paying a cost that is increasing in the pollution level and decreasing in the natural capability of agents to resist to diseases. The pollution level affects directly the number of agents who get sick. We have analyzed the case of a private duopoly and the case of a mixed one, comparing results. Therefore, we have analyzed the double chance, by the government, to set the optimal pollution level and to have or not a public firm in the market.

We find that the presence of the public firm makes the government to accept a higher pollution level that implies a higher number of sick agents with respect to the private duopoly model. However, the public firm also guarantees a lower unserved market share, a higher quality spread and a higher average quality(both in the case where it offers the high and the low quality service).

Since the medical care service is a market with specific features because it regards the life of agents and not only their consumption choices, we have also adopted a different approach in order to evaluate the scenario with the lowest number of agents who have some clinical complications or perish. To do this, we have assumed that the quality level affects the mortality rate depending on the degree of the quality effectiveness to fight the illness. By doing so we try to mitigate the resulting trade off between the high pollution level in the mixed duopoly and the low average quality in the private one. The result is that the private duopoly becomes preferred to the mixed one if only if the quality effectiveness is very low.

In both evaluations, for a level of quality effectiveness that is not very low, the preferred scenario is the mixed duopoly with the public firm offering the high quality service and the private firm offers the low one.

To conclude, the mixed duopoly with the public firm offering the high quality service is the market configuration which implies not only the highest welfare level, but also the lowest risk of perishing for sick agents, except for cases of a very low quality effectiveness of the medical care service, like for very common diseases or, probably, in developing countries.

References

[1] Bjorvatn A. (2018), "Private or public hospital ownership: Does it really matter?" *Social Science & Medicine*, 196: 166-174, January.

[2] Briggs D. (2003), "Environmental pollution and the global burden of disease." *British Medical Bulletin*, 68: 1-24.

[3] Brockmeyer S. and D'Angiulli A. (2016), "How air pollution alters brain development: the role of neuroinflammation." *Translational Neuroscience*, 7 (1): 24-30, March.

[4] Calderón-Garcidueñas L., Torres-Jardón R., Kulesza R. J., Park S.-B., and D'Angiulli A. (2014), "Air pollution and detrimental effects on children's brain. The need for a multidisciplinary approach to the issue complexity and challenges." *Frontiers Research Foundation*, 8 (613), August.

[5] Delbono F., Denicolò V. and Scarpa C. (1996), "Quality choice in a vertically differentiated mixed duopoly." *Economic Notes by Banca Monte dei Paschi di Siena SpA*, 25 (1): 33-46.

[6] Ebenstein A., Fan M., Greenstone M., He G., Yin P. and Zhou M. (2015), "Growth, Pollution, and Life Expectancy: China from 1991-2012." *American Economic Review*, American Economic Association, 105(5): 226-231, May.

[7] Gabszewicz J. and Thisse J.-J. (1979), "Price Competition Quality and Income Disparities." *Journal of Economic Theory*, 20: 340-359.

[8] Gaynor M. and Town R. J., (2011), "Competition in Health Care Markets." *NBER Working Paper* No. 17208.

[9] Gravelle H., Santos R. and Siciliani L. (2014), "Does a hospital's quality depend on the quality of other hospitals? A spatial econometrics approach." *Regional Science and Urban Economics*, 49: 203-216, November.

[10] Grilo I. (1994), "Mixed duopoly under vertical differentiation." *Annales d'Économie et de Statistique*, 33: 91-112, January-March.

[11] Gutacker N., Siciliani L., Moscelli G. and Gravelle H. (2016), "Choice of hospital: Which type of quality matters?" *Journal of Health Economics*, 50: 230-246, December.

[12] Harris M. H., Gold D. R., Rifas-Shiman S. L., Melly S. J., Zanobetti A., Coull B. A., Schwartz J. D., Gryparis A., Kloog I., Koutrakis P., Bellinger D. C., Belfort M. B., Webster T. F., White R. F., Sagiv S. K., and Oken E. (2017), "Prenatal and Childhood Traffic-Related Air Pollution Exposure and Childhood Executive Function and Behavior." *Neurotoxicology and Teratology*, 57: 60-70.

[13] Ishibashi K. and Kaneko T. (2008), "Partial privatization in mixed duopoly with price and quality competition." *Journal of Economics*, 95: 213-231.

[14] Jofre-Bonet M. (1999), "Health care: private andror public provision." *European Journal of Political Economy*, 16: 469-489, September.

[15] Lambertini L. (1996), "Choosing roles in a duopoly for endogenously differentiated products." *Australian Economic Papers*, 35: 205-24.

[16] Liu L. and Lu Y. (2012), "Endogenous timing in a mixed duopoly with endogenous vertical differentiation." *Bulletin of Economic Research*, 66 (3): 0307-3378

[17] Lutz S. and Pezzino M. (2014), "Vertically differentiated mixed oligopoly with quality-dependent fixed costs." *The Manchester School*, 82 (5): 596-619, September.

[18] Moorthy K. S. (1988), "Product and price competition in a duopoly." *Marketing Science*, 7 (2): 141-169.

[19] Motta M. (1993), "Endogenous quality choice: price vs. quantity competition." *The Journal of Industrial Economics*, 41 (2): 113-131.

[20] Preker A., Adeyi O., Lapetra M. G., Simon D. C., Keuffel E. (2016), "Health Care Expenditures Associated With Pollution: Exploratory Methods and Findings." *Annals of Global Health*, 82 (5): 711-721, September - October.

[21] Propper C., Sutton M., Whitnall C. and Windmeijer F. (2008), "Did 'Targets and Terror' Reduce Waiting times in England for Hospital Care?" *The B.E. Journal of Economic Analysis & Policy*, De Gruyter, vol. 8 (2): 1-27, January.

[22] Shaikh M, Miraldo M, Renner A-T (2018) Waiting time at health facilities and social class: Evidence from the Indian caste system. *PLoS ONE* 13(10)

[23] Shaked A. and Sutton J. (1982), "Relaxing price competition through product differentiation." *Review of Economic Studies*, 49 (1): 3-13.

[24] Tay A. (2003), "Assessing Competition in Hospital Care Markets: the Importance of Accounting For Quality Differentiation." *Rand Journal of Economics*, 34 (4): 786-814.

[25] Tynkkynen L.-K. and Vrangbæk K. (2018), "Comparing public and private providers: a scoping review of hospital services in Europe." *BMC Health Services Research*, 18: 141, February.

[26] Wauthy X. (1996), "Quality Choice in Models of Vertical Differentiation." *The Journal of Industrial Economics*, 44 (3): 345-353.

8 Appendices

8.1 Appendix 1. Conditions for concavity in the quality stage in the private duopoly

The SOC of the high quality firm requires:

$$\frac{\partial^2 \pi_H}{\partial^2 \theta_H} = -2q \frac{20\theta_H \theta_L^2 + 4\theta_L^3 + 17k^2\theta_H\theta_L^4 + 48k\theta_H^2\theta_L^2 - 44k\theta_H\theta_L^3 + 160k^2\theta_H^4\theta_L - 128k\theta_H^3\theta_L - 40k^2\theta_H^3\theta_L^2 - 192k^2\theta_H^5 + k^2\theta_L^5 + 128k\theta_H^4 - 4k\theta_L^4}{(\theta_L - 4\theta_H)^4} < 0$$

whereas the SOC of the low quality firm is satisfied if:

$$\frac{\partial^2 \pi_L}{\partial^2 \theta_L} = -2q\theta_H \frac{96k^2\theta_H^2\theta_L^2 + 7\theta_H\theta_L + 40k^2\theta_H^4 + 48k\theta_H^3 + k^2\theta_L^4 + 8\theta_H^2 - 121k^2\theta_H^3\theta_L - 16k^2\theta_H\theta_L^3 - 66k\theta_H^2\theta_L}{(\theta_L - 4\theta_H)^4} < 0.$$

Since the equilibrium qualities are

$$\theta_H^* = \frac{0.40972}{k} \text{ and } \theta_L^* = \frac{0.19936}{k}$$

the SOCs are locally satisfied as

$$\begin{aligned} \frac{\partial^2 \pi_H \left(\theta_H = \frac{0.40972}{k}, \theta_L = \frac{0.19936}{k}\right)}{\partial^2 \theta_H} &= -0.449\, kq < 0 \\ \frac{\partial^2 \pi_L \left(\theta_H = \frac{0.40972}{k}, \theta_L = \frac{0.19936}{k}\right)}{\partial^2 \theta_L} &= -0.585\, kq < 0 \end{aligned}$$

since k and q are positive.

8.2 Appendix B. The concavity conditions in the quality stage in Scenario A

The SOC of the private firm, which offers the high quality good, requires:

$$\frac{\partial^2 \pi_H}{\partial^2 \theta_H} = -2\frac{q}{(\theta_L - 2\theta_H)^4} \begin{pmatrix} -12k^2\theta_H^5 + 16k^2\theta_H^4\theta_L - 2k^2\theta_H^3\theta_L^2 - 6k^2\theta_H^2\theta_L^3 + 7k^2\theta_H\theta_L^4 + k^2\theta_L^5 + \\ +8k\theta_H^4 - 16k\theta_H^3\theta_L + 12k\theta_H^2\theta_L^2 - 8k\theta_H\theta_L^3 - 2k\theta_L^4 + \theta_H\theta_L^2 + \theta_L^3 \end{pmatrix} < 0$$

The SOC of the public firm, which offers the low quality good, is satisfied if:

$$\frac{\partial^2 W_L}{\partial^2 \theta_L} = -q\frac{\theta_H}{(\theta_L - 2\theta_H)^4} \begin{pmatrix} 11k^2\theta_H^4 - 40k^2\theta_H^3\theta_L + 48k^2\theta_H^2\theta_L^2 - 16k^2\theta_H\theta_L^3 + 2k^2\theta_L^4 + 10k\theta_H^3 \\ -14k\theta_H^2\theta_L - \theta_H^2 + 2\theta_H\theta_L \end{pmatrix} < 0$$

For the given equilibrium qualities

$$\theta_H^* = \frac{0.37995}{k} \text{ and } \theta_L^* = \frac{0.25882}{k}$$

the SOCs are locally satisfied as

$$\begin{aligned} \frac{\partial^2 \pi_H \left(\theta_H = \frac{0.37995}{k}, \theta_L = \frac{0.25882}{k}\right)}{\partial^2 \theta_H} &= -0.595\, kq < 0 \\ \frac{\partial^2 W_L \left(\theta_H = \frac{0.37995}{k}, \theta_L = \frac{0.25882}{k}\right)}{\partial^2 \theta_L} &= -0.644\, kq < 0 \end{aligned}$$

since k and q are positive.

8.3 Appendix C. The concavity conditions in the quality stage in Scenario B

The SOC of the private firm, which offers the low quality good, requires:

$$\tfrac{\partial^2 \pi_L}{\partial^2 \theta_L} = -6k^2 q \theta_H^4 \tfrac{\theta_L}{(\theta_L - 2\theta_H)^4} < 0$$

which is always verified, because q and θ_L are positive.

The SOC of the public firm, which offers the high quality good, is satisfied if:

$$\tfrac{\partial^2 W_H}{\partial^2 \theta_H} = -k \tfrac{q}{(\theta_L - 2\theta_H)^4} \left(\begin{array}{c} -48k\theta_H^5 + 84k\theta_H^4 \theta_L + 32\theta_H^4 - 48k\theta_H^3 \theta_L^2 \\ -64\theta_H^3 \theta_L + 6k\theta_H^2 \theta_L^3 + 48\theta_H^2 \theta_L^2 + 3k\theta_H \theta_L^4 - 16\theta_H \theta_L^3 + 2\theta_L^4 \end{array} \right) < 0$$

For the given equilibrium qualities

$$\theta_H^* = \frac{0.389\,83}{k} \text{ and } \theta_L^* = \frac{0.259\,89}{k}$$

the SOC of the welfare maximization is locally satisfied as

$$\frac{\partial^2 W_H \left(\theta_H = \frac{0.389\,83}{k}, \theta_L = \frac{0.259\,89}{k}\right)}{\partial^2 \theta_H} = -0.648\, kq < 0$$

since k and q are positive.