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INVESTMENT IN HEALTH TECHNOLOGIES IN A COMPETITIVE MODEL WITH REAL OPTIONS

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Investment in health technologies in a competitive model with real options[‡]

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Abstract

This paper studies the optimal timing of investment in innovative technology by health care providers competing for patients, in a real option framework. The innovative technology provides a better health outcome, thus attracting a larger number of patients. On the other hand, at the early stages of innovation it is assumed to involve a larger degree of uncertainty and higher operational costs. Since further development of the technology is expected to improve efficiency over time, each provider faces a trade-off between gaining a competitive advantage by investing first, and fully exploiting the option to delay investment under uncertainty. The model is set up so that the role of the payment system on investment decisions may be investigated. This turns out not to be always intuitive. In particular, it is showed that a more generous scheme does not always induce to anticipate investment. By comparing the competitive solution with the social optimal timing, some policy implications are finally discussed.

1 Introduction

After an increasing number of countries have reformed health care systems with the aim of increasing efficiency, the issue of quality of the services provided has been among the most debated. This concern arises from the observation that the tendency underlying most reforms has been to separate the role of the provider from that of the purchaser of the services, and to shift from mainly cost-based to mainly prospective reimbursement systems. A first approach to the issue of investment in quality of the health services is focused on the relationship specific characteristics that may lead to the 'hold-up' problem[1]. The

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[‡]This paper is an extract from the preliminary version of my Phd thesis (Supervisors: R. Levaggi and M. Moretto).

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[1]The idea was first developed by Klein et al. (1978) and Williamson (1975).

prediction from this literature is of inefficiently low investments in quality.

On the other hand, other contributions have emphasized the role of the incentives to invest in quality for providers that are no longer monopolists (Weisbrod, 1991) and compete for patients in a prospective payment system. The pressure may be strong because patients, unlike most consumers, rarely pay out of pocket the full cost of the services they receive. The prediction in this case is reversed, the tendency being to over-investment in quality.

Such sharp differences in the predictions from alternative models may seem misleading. In fact, the two approaches make somehow extreme assumptions on the competitive structure of the market for health care services. Whereas in the 'hold-up' case the attention is restricted to the contractual relationship, in models where the incentive to over-investment is emphasized the competition among providers is the leading force for the investment decisions, because patients can observe quality of services and decide accordingly, without paying out of pocket for higher quality levels. That patients can observe quality of medical services overall is hard to claim, and it is also clear that health care providers are to some extent subject to competitive pressures. However, the insights of both these approaches may be relevant if quality is seen as a multidimensional attribute (Chalkley and Malcomson, 1998), and the different dimensions differ in terms of observability, thus creating different degrees of competitive pressures.

A further source of incentives for providers is the payment system. The tendency in recent years has been to move from cost reimbursement toward prospective payment. An interesting issue then, is how payment systems should be designed to create appropriate incentives for hospitals that face also competitive pressures[2]. The common belief is that more generous payments to the provider create an incentive toward the adoption of new technologies Cutler and McClellan (1996).

The aim of the present paper is to concentrate on the incentives to invest in the specific dimension of quality that is connected to technology, which is probably among the main determinants of the health outcome. The opinion that technological innovation boosts health care costs is widespread and it has also been tested empirically[3]. The analysis in the paper best fits the issue of investment in equipment. The distinguishing characteristic of this kind of investment in medical technology when compared with other dimensions of quality is that it is a long term irreversible decision, which has typically to be taken under uncertainty. Therefore, the intertemporal dimension of the decision becomes a key issue. Although the need to extend the anaysis of investment in medical technologies to account for the intertemporal and competitive dimension has been pointed out (Chernew et al., 2001) the issue has almost invariably been addressed in static settings.

Bos and De Fraja (2002) set up a model where the investment in non-contractible quality is irreversible. They do not model competition explicitly, but they allow

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[2]See, for example, Ellis (1998).

[3]Cutler and McClellan (1996) for example, find evidence of the role of the diffusion of new technologies in the increase in cost.

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the purchaser to invest in outside capacity. In this context, although the investment is relationship specific, investments by the purchaser and the provider are substitutes, rather than complements, as it is typically the case in hold-up models, and the outcome is over-investment instead of under-investment.

Levaggi and Moretto (2004) study the decision to invest in innovative technology with uncertain returns, in a genuinely dynamic setting. Their analysis is developed within a real options framework, following the insight by Palmer and Smith (2000) on the opportunity to extend the evaluation of health care technologies to take the value of the options possibly embodied in the investment project into account. They show that long-term contracts are most effective in creating incentives for a representative provider to invest in innovative technologies.

As it has been discussed above, competitive pressures may play a key role in investment decisions as long as these have an impact on the strategic position. This will be the case, for instance, when the ability to attract patients is enhanced. In the present paper, as in Levaggi and Moretto (2004) a real option approach is adopted, but the model is extended to allow for two providers competing for patients. The investment decision is assumed discrete, so that the focus is on the timing rather than on the level of investment. In real life, the decision maker may actually face situations where the question is whether, and in case when, to invest in an innovative technology rather than how much to invest. The model is mainly based on that part of the literature on real options that investigates the role of competition in influencing these decisions, through game theoretic models[4]. The idea behind the real options approach is that the 'naive' approach to capital budgeting under uncertainty based on the expected Net Present Value (NPV) fails to take into account the opportunity to adjust investment decisions over time, as uncertainty is resolved. In other words, the NPV approach implicitly assumes that the investment decision is either 'now or never', or not irreversible. More recently, it has been underlined that the optimal investment decision in this perspective may not be only dependent on the characteristics of uncertainty, but also on strategic interactions. This is the case, for instance, when an option is shared rather than private, so that if the competitor exercises it first the option is no longer available, or its value reduced.

The objective of the paper is to investigate the investment decision in innovative health technology studying the interaction between option values and competitive forces, whose role in the investment decision process has been underlined in the literature referred to above. This has actually an impact on the equilibrium outcomes, that are of two types. In the first case, the advantage of becoming the leader is large enough that both competitors aim to preempt the other and end up in a sequential equilibrium. In the second case, investing simultaneously is more valuable and investment by both will be delayed relative to the first case. The payment system affects the timing of adoption both within each class of equilibria, and by determining whether the equilibrium will be sequential or

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[4]Huisman (2001) provides a comprehensive overview.

simultaneous. In particular, it is showed that when this is taken into account, more generous payment systems do not necessarily induce providers to anticipate investment.

In the model, competitive investment may happen both later and earlier than the social optimum. What the case will be depends on several parameter values, including the propensity by patients to incur additional costs to seek better technology. If the regulator may distinguish among treatments in this respect, then the payment system may be adapted in order to induce a timing of investment with similar characteristics to the social optimal timing.

In the first section, the competitive model is introduced. The optimal strategies and the equilibrium outcomes of the game are presented in Section 3. The following section investigates the role of the payment scheme in the investment decision. In Section 5 the timing of investment corresponding to the equilibrium outcome under competition is compared with the social optimum. This provides the basis for the discussion of some mainly qualitative policy implications. In particular, the focus is on what characteristics of the payment scheme may reduce the distortions that the competitive pressures induce.

2 The Model

2.1 Patients

Let two hospitals competing for patients be placed at the extremes of a line of unit length (Ellis, 1998; Beitia, 2003). The number of people that require the treatment is assumed fixed and normalized to one. Fully ensured patients are free to decide where to seek care. Let d be the distance from the origin and $1/\delta$ the unitary cost of transport. The latter parameter may be more usefully interpreted as a (inverse) measure of elasticity of demand that may vary considerably, depending on the type of treatment needed. For example, this may be close to infinity for some emergencies. The benefit the patient receives from treatment depends on the technology available in the hospital were she is treated. This is described as discrete, the alternative being between basic technology, providing benefit B_0 and innovative technology, with associated benefit B_1, such that $B_1 > B_0$. The level of benefit is assumed independent of the number of patients treated by each provider.

If technology is observable ('selected referral' hypothesis), fully ensured patients maximize the benefits from treatment, net of transportation costs. As it has been discussed above, the assumptions that are made on observability of quality are crucial in determining the level of investment. Since mechanisms of referral are operating in most systems, it seems natural in this context to assume that technology, unlike other dimensions of quality, is observable. Equating the net benefit of seeking care from the two hospitals, the location of the marginal patient is obtained:

$$d^* = \frac{1}{2} + \frac{\delta}{2}\left(B_i - B_j\right) = x_{ij} \tag{1}$$

where, subscripts i and j denote respectively the technology adopted by the provider placed in the origin and at the other extreme, which may be either basic $(i, j = 0)$ or innovative $(i, j = 1)$. Given the assumptions on the distribution of the patients along the line, this is also the number of patients treated by the provider whose technology is i, when the competitor uses technology j. Since the technology can only be basic or innovative, there are only four possible levels of demand for each provider. Assuming that providers are symmetric with respect to any aspect other than technology, each of them faces one of the following levels of demand:

$$x_{00} = x_{11} = \frac{1}{2}$$

$$x_{10} = min \left\{ \frac{1}{2} + \frac{\delta}{2} (B_1 - B_0), 1 \right\} \tag{2}$$

$$x_{01} = max \left\{ \frac{1}{2} - \frac{\delta}{2} (B_1 - B_0), 0 \right\}$$

It is assumed throughout that also the basic technology ensures for all patients net benefits that exceed reservation utility.

2.2 Providers

In order to keep the analysis as simple as possible, providers are assumed to be pure profit maximizers:

$$V_{ij} = x_{ij} [p + (r - 1)c_i] \tag{3}$$

where, p and r indicate respectively the price and cost-reimbursement component of the payment scheme (Ellis and McGuire, 1986). The price is set independently of the technology employed, thus reflecting inability or reluctance of the purchaser to discriminate different technological levels as long as the treatment is perceived to be the same despite the difference in the technological content. For the sake of simplicity, the possibility that the benefits enjoyed by patients directly enter in the providers' objective function is ignored in the basic model[5]. The main implications of adding a pure benefit component to the hospitals' payoff functions will be discussed in Section 5.

The key variable in the model is the marginal cost, which is assumed independent of the number of patients treated, but technology dependent. In particular, it is assumed in the baseline model that under the basic technology hospitals face a marginal cost that is also time invariant (c_0). The marginal cost of the innovative technology, instead, is assumed stochastic, following a geometric brownian motion:

$$dc(t) = \mu c(t) dt + \sigma c(t) dw(t) \tag{4}$$

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[5]This assumption is often made in the health economics literature. It is also generally agreed that the impact on conclusions is usually minor. See for example (Danzon, 1982; Dranove and White, 1994).

where, $\mu < 0$ is the drift component and dw is the increment of a Wiener process. Thus $dw(t)$ is distributed according to a normal distribution with mean zero and variance dt.

The assumption that the marginal cost is constant across time for the old technology, whereas it varies according to the brownian motion for the innovative one is connected to the observation that the degree of uncertainty tends to be reduced as innovative technologies spread. In particular, it looks reasonable that further research aimed at improving performances is most likely to be successfully carried out at the early stages of the development of an innovative technology. This is reflected in the brownian motion with negative drift, where the absolute value of the rate of decline of $c(t)$ decreases with time. Underlying is the assumption that the alternative technologies employ, at least to some extent, different inputs.

For the sake of simplicity it is also assumed throughout that:

$$c(0) > \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{10}}\right)\left(\frac{p(x_{10} - x_{00}) - \rho I}{1 - r} + x_{00}c_0\right) \qquad (5)$$

This condition rules out situations where immediate investment is the optimal strategy[6].

Emphasizing the role of uncertainty over marginal cost seems particularly relevant in the health sector, where it is not rare, unlike in most other sectors, that innovations raise costs. An example of innovative technology that is currently spreading, whose marginal costs exceed by far those of its substitutes is the Positron Emission Tomography. In that case, the radiopharmaceutical to be used in the examination accounts for a large part of the total marginal cost. Consistently with the assumptions introduced above, this cost has been declining over time and this trend may be reasonably assumed to continue in the future as a result of the increasing number of centres producing it and the intense research on alternative production technologies.

The payoff functions for the different competitive situations are the following:

$$
\begin{aligned}
V_{00} &= x_{00}\left[p + (r-1)c_0\right] \\
V_{01} &= x_{01}\left[p + (r-1)c_0\right] \\
V_{10} &= x_{10}\left[p + (r-1)c(t)\right] \\
V_{11} &= x_{11}\left[p + (r-1)c(t)\right]
\end{aligned}
$$

A non-negative profit condition for the basic technology is also assumed:

$$p + (r-1)c_0 \geq 0$$

Since the payoff the providers get before they adopt the innovative technology is in general different from zero, the model belongs to the class of 'existing market' models, as opposed to 'new market models' (Dixit and Pindyck (1994)). The

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[6]The meaning of this condition will become apparent in Section 3.1.

problem for each provider is to decide when to invest in the new technology. The investment allows to increase the number of patients treated, according to the model outlined above, and hence revenues, but implies that the marginal cost of each treatment provided becomes stochastic and, in expected terms, it is higher the earlier the time of adoption. It follows that in the model the determination of the number of patients that chooses each hospital is static, whereas the investment decision is dynamic. The *optimal stopping* problem is solved assuming risk neutrality for both providers.

3   The stocastic case

When the variation of c over time is stochastic and follows the geometric brownian motion (4), each provider faces the alternative between sticking to the basic technology and thus incurring the constant marginal cost c_0 and a level of demand that never exceeds one half but may fall to x_{01} if the competitor invests first, or investing in the new technology, thus facing uncertainty on $c(t)$. This is a typical *optimal stopping* problem: at each point in time the investor observes the value of the stochastic variable whose process is known and decides whether to invest or not. If providers were free from competitive pressures, the adoption of a real option approach would lead to delay investment in comparison with the optimal timing under the NPV approach, as a result of the value attributed to the option to wait. When there is competition over patients, the value of this option may not be fully exploited because the risk of bearing the cost of the negative externality associated to the competitor's entry creates an incentive in the opposite direction.

The problem is solved backwards. First, competitors are assumed to be pre-committed to a role (leader or follower) and the optimal threshold of the stochastic variable is determined. This is done starting from the decision for the follower under the assumption that the leader has already invested. Once the optimal reaction is determined, the leader is assumed to optimally choose the time of adoption, anticipating it. This also allows to fully characterize the value functions for both roles under each strategic situation. Finally, the precommitment hypothesis is relaxed and hospitals are allowed to compete for the most valuable role.

3.1   Pre-commitment equilibrium

3.1.1   The follower

Under the assumption that the leader has already invested, the solution of the follower's optimal stopping problem is identical to that of a monopolist that adopts a real option approach. As a result of the irreversibility of investments, the value function in the stopping region (after investment) is just the expected value of future returns (see Appendix A):

$$F_{11}(c) = \frac{x_{11}p}{\rho} + \frac{(r-1)x_{11}c}{\rho - \mu} - I \qquad (7)$$

In the continuation region (before investment) the value is the sum of the expected value under the *status quo*, plus the value of the opportunity to invest (see Appendix A):

$$F_{01}(c) = A_2 c^{\beta} + \frac{x_{01}p + (r-1)x_{01}c_0}{\rho} \qquad (8)$$

where, $\beta < 0$ is the negative root of the following second order equation:

$$\frac{1}{2}\sigma^2\beta^2 + \left(\mu - \frac{1}{2}\sigma^2\right)\beta - \rho = 0 \qquad (9)$$

Each of the two value functions (7) and (8) specified above is relevant for a range of values of the stochastic variable c. Hence, the follower's value function may be rewritten with more compact notation:

$$F(c) = \begin{cases} A_2 c^{\beta} + \frac{x_{01}p + (r-1)x_{01}c_0}{\rho} & \text{for } c > c_F \\ \frac{x_{11}p}{\rho} + \frac{(r-1)x_{11}c}{\rho - \mu} - I & \text{for } c \leq c_F \end{cases} \qquad (10)$$

The standard approach to the solution of the optimal stopping problem is to impose the 'value matching' and 'smooth pasting' conditions at the point where it is optimal to invest, that is, the threshold value of the stochastic variable. The first condition is quite intuitive, as it simply requires the value functions before and after investment to match at the value of the stochastic variable for which it is optimal to invest. The 'smooth pasting condition' also requires these functions to have the same slope at the point where they match[7].

These conditions enable to determine the optimal threshold for the follower (c_F) and the value of the constant still to be determined:

$$c_F = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{11}}\right)\left(\frac{p(x_{11} - x_{01}) - \rho I}{1 - r} + x_{01}c_o\right) \qquad (11)$$

$$A_2 = \frac{c_F^{1-\beta}}{\beta}\left(\frac{x_{11}(r-1)}{\rho - \mu}\right) \qquad (12)$$

The reason why a positive term $(A_2 \geq 0)$ is added to the expected value component in F_{01} is that the follower has the right but not the obligation to invest. In the mean time, no strategic power is left to the leader after the follower's irreversible investment.

The first term in the expression for c_F picks up the impact of taking the value of the option to delay investment into account. Since β is negative, that term is positive and smaller than one in absolute value. Hence, the threshold is reduced

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[7]For a comprehensive discussion of this condition, see Dixit and Pindyck (1994).

and investment, in expected terms, delayed[8]. This effect is larger, the greater the volatility component (σ) of the stochastic variable[9].

The effect of an increase in the price component of the payment scheme is to increase the threshold. As expected then, this induces earlier investment although, for a given number of patients treated, the treatment provided with the basic technology also becomes more profitable. The effect of an increase in r instead is less intuitive. Equation (11) shows that the effect on the the threshold is consistent with that of an increase in price only as long as $p(x_{11} - x_{01}) - \rho I > 0$. Since the effect of an increase in r is to increase the absolute value of the ratio, this effect may take opposite signs depending on the sign of the numerator. When the expected gain in revenues is not large enough to compensate for the cost of the investment, a more generous scheme in the form of a higher reimbursement component increases the relative profitability of the basic technology. From the payer's standpoint this has a further implication: for combinations of the parameters such that $p(x_{11} - x_{01}) - \rho I < 0$, an increase of the price component combined with a reduction of the cost-reimbursement component may induce a costless increase in the follower's threshold[10].

3.1.2 The Leader

As for the follower, the optimal stopping problem is first solved assuming that the leader's role is assigned beforehand. The main difference in this case is that there will be three ranges of values relevant for the value function, corresponding to the regions where neither ($L_{00}(c)$), the leader only ($L_{10}(c)$), and both ($L_{11}(c)$) have invested. From the corresponding Bellman equations, the following value function is obtained for the leader (see Appendix A):

$$L(c) = \begin{cases} K_2 c^\beta + \frac{x_{00}p}{\rho} + \frac{(r-1)x_{00}c_0}{\rho} & \text{for } c \geq c_L \\ E_2 c^\beta + \frac{x_{10}p}{\rho} + \frac{(r-1)x_{10}c}{\rho - \mu} - I & \text{for } c_F < c < c_L \\ \frac{x_{11}p}{\rho} + \frac{(r-1)x_{11}c}{\rho - \mu} - I & \text{for } c \leq c_F \end{cases} \quad (13)$$

where, the value of the constants obtained imposing the 'value matching' and 'smooth pasting' conditions is:

$$E_2 = c_F^{-\beta} \left[\frac{p}{\rho} + \frac{c_F(r-1)}{\rho - \mu} \right] (x_{11} - x_{10}) \leq 0 \quad (14)$$

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[8]It is more standard in the literature to find an increasing effect of the option component on the threshold in models where the stochastic variable with a positive drift is a positive component in the objective function. In such cases it is optimal to invest for values at least as large as the threshold. Since the drift component is negative in our model, the two results are perfectly consistent in terms of expected time, in the sense that in both cases the option component tends to delay the investment.

[9]It may be checked from the solution of equation (9) that increases in σ yield larger values of β (smaller in absolute terms).

[10]Of course, as it will be seen in the welfare analysis, this is not always desirable from the standpoint of an hypothetical social planner.

$$K_2 = E_2 + \frac{x_{10}(r-1)}{\rho - \mu} \left(\frac{c_L^{1-\beta}}{\beta} \right) \tag{15}$$

As it is obvious, the value functions coincide for the leader and the follower after both have adopted the new technology ($L_{11} \equiv F_{11}$ for $c \leq c_F$). The structure of the other two functions is similar to that of $F_{01}(c)$, consisting of the expected value under the *status quo*, plus an exponential term. As discussed above, in $F_{01}(c)$ this may be interpreted as the value of the opportunity to invest. For the leader, the interpretation is somehow more involved, because this term has also to account for the follower's option to invest, which is a negative component from the leader's standpoint. Since the investment is irreversible, after the leader has invested, there is only an option available to the follower, whose decision to invest depends on the value of the stochastic variable. The exercise of such option creates a negative externality for the leader, so that its value in this region must be smaller than the expected value under the current strategic situation. This is what the exponential term in $L_{10}(c)$ picks up.

Going backwards, before the leader's investment the option value includes the opportunity to exploit the competitive advantage that in the pre-commitment setting is exogenously assigned. This will be a positive value (second term in K_2). However, the option value that is relevant in this region must also anticipate the opportunity for the follower to respond to the leader's investment canceling this advantage. Hence, the option value component in $L_{00}(c)$ may be interpreted as the value of the opportunity to invest for the leader, net of the externality associated to the opportunity for the follower to invest.

The usual boundary conditions allow to determine the optimal threshold for the leader's investment:

$$c_L = \left(\frac{\beta}{\beta - 1} \right) \left(\frac{\rho - \mu}{\rho} \right) \left(\frac{1}{x_{10}} \right) \left(\frac{p(x_{10} - x_{00}) - \rho I}{1 - r} + x_{00} c_0 \right) \tag{16}$$

The effect of changes in the payment scheme parameters is symmetric to the follower's case. Also the effect of variations in the other parameters is intuitive. The effect of the term including β is proportional. This means that in the standard case where $c_L > c_F$, taking the option to dealy investment into account tends to reduce the gap between the thresholds relative to the case where the decision criterion is the expected net present value. This is the opposite of what happens in those cases where the relevant β is larger than one, and a larger threshold ($\beta/(\beta - 1) > 1$) corresponds to a delayed investment.

The equilibrium under pre-committment is straightforward: the leader adopts the technology at time T_L, whereas the follower adopts in T_F, where:

$$\begin{aligned} T_L &= min\,(t\,|c \leq c_L) \\ T_F &= min\,(t\,|c \leq c_F) \end{aligned} \tag{17}$$

The comparison of the thresholds for the leader and the follower shows that in principle either may be larger. If $c_F > c_L$, since the follower is committed to invest only after the leader, its investment will occur just after that ('cascade').

The equilibrium in this case involves simultaneous investment: the leader invests at T_L and the follower immediately afterwords. As it is usually done in the literature on strategic option games, in the rest of the paper we ignore this case, assuming that there is some kind of first-mover advantage. In the standard model discussed in the literature, where the payoff function is the product of the stochastic variable and a deterministic part, this is ensured by a very simple condition on the deterministic part of the function. In our model this may not be ensured by such a simple condition. A formal condition is presented in Appendix A, where it is also showed that 'cascades' are less likely to happen when payment schemes are relatively less generous.

3.1.3 Simultaneous investment

As will be clear from the next section, for a full analysis of the equilibria, the study of the optimal timing of investment under the hypothesis that the providers are committed to invest at the same time is also needed. Technically speaking, this analysis is identical to a monopoly problem, the relevant payoffs before and after investment being respectively V_{00} and V_{11}. The value functions in the corresponding regions will be denoted by $J_{00}(c)$ and $J_{11}(c)$. The compact form of the value function for the simultaneous investment is (see Appendix A):

$$J(c) = \begin{cases} D_2 c^\beta + \frac{x_{00}p}{\rho} + \frac{(r-1)x_{00}c_0}{\rho} & \text{for } c > c_J \\ \frac{x_{11}p}{\rho} + \frac{(r-1)x_{11}c}{\rho-\mu} - I & \text{for } c \leq c_J \end{cases}$$

Imposing the usual boundary conditions, the values of the constant D_2 and of the threshold are determined:

$$D_2 = \frac{c_J^{1-\beta}}{\beta}\left(\frac{x_{11}(r-1)}{\rho-\mu}\right) \tag{19}$$

$$c_J = \left(\frac{\beta}{\beta-1}\right)\left(\frac{\rho-\mu}{\rho}\right)\left(\frac{1}{x_{11}}\right)\left(x_{00}c_0 - \frac{\rho I}{1-r}\right) \tag{20}$$

The optimal time for simultaneous investment is T_J, which is defined as usual:

$$T_J = min\left(t \,|c \leq c_J\right)$$

A first difference with individual strategies is that, as it is immediate to observe in (19) and (20), the optimal timing of simultaneous investment is completely independent of p. It is also straightforward to prove that the threshold for joint investment is always smaller than the thresholds of the leader and the follower. Hence, the optimal simultaneous strategy involves delayed investment. Finally, eq. (20) shows that in this case an increase in the cost reimbursement component always delays investment.

3.2 Endogenous roles

The assumption that competitors are pre-committed to be either the leader or the follower is obviously artificial for most situations in real life. In this section, hospitals are finally allowed to decide if and when to invest in the new technology, taking also into account how their own decision will influence the competitor's strategy. Fudenberg and Tirole (1985) show that moving from discrete to continuous time framework, the concept of sub-game perfection developed in the first setting is not sufficient to fully characterize the equilibria. Therefore, in principle a game in continuous time may not be solved as the limit of the discrete time case. The extension of the concept provided by Fudenberg and Tirole allows a complete analysis of mixed strategies for symmetric players. Equilibrium outcomes, however, turn out to be equivalent to the case where players adopt pure strategies but may take on different roles. For the sake of simplicity, then, as it is often done in the literature on strategic option games, we exploit this coincidence in outcomes to restrict attention to pure strategies in what follows.

The complete description of the closed-loop equilibrium requires two alternative cases to be separately discussed:

Case a): $\exists c > c_F \, | \, L(c) > J(c, c_J)$

By $J(c, c_J)$, we denote the value of simultaneous investment when the value of the stochastic variable is $c(t)$, under the assumption that providers will invest in T_J.

Figure 1: Case a
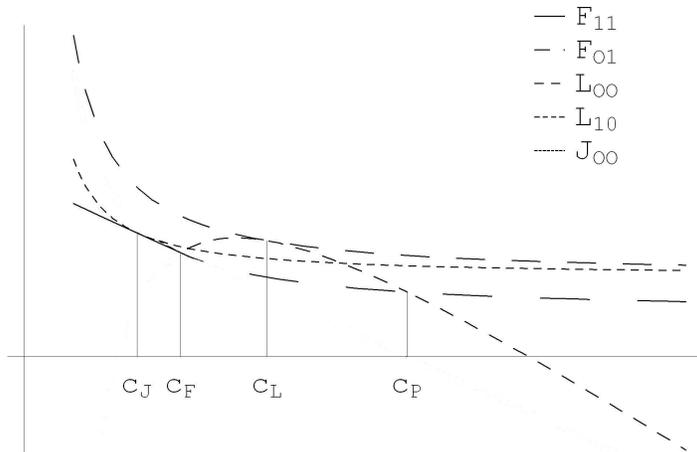
It may be proved (Appendix A) that $L_{10}(c_L) > F_{01}(c_L)$. Hence, at the time

when it is optimal for the leader to invest, investing first is more convenient than waiting. Moreover, by definition of *Case a*, there is a range of values of the stochastic variable that includes the threshold c_L, where the value of the leader exceeds that of the optimal joint investment. Starting from c_L, under the assumption that neither competitor has invested yet, there is no incentive to wait longer. On the contrary, the value being strictly larger for the leader than for the follower and roles being now endogenous, there will be an incentive to preempt the other investing in $c_L + \epsilon$. The optimal response to this will be re-setting the threshold again to $c_L + 2\epsilon$. Such an incentive will exist as long as $L_{10}(c) = F_{01}(c)$, which occurs in c_P[11] (Fig.1).

Let us define,

$$
\begin{aligned}
c_P &= max\left(c\,|L_{10}(c) \geq F_{01}(c)\right) \\
T_P &= min\left(t\,|c \geq c_P\right)
\end{aligned}
$$

The equilibrium is than the following:

In Case a, the only equilibrium is sequential. The leader invests in T_P, the follower in T_F.

Case b): $\forall c > c_F, J(c, c_J) \geq L(c)$

Figure 2: Case b
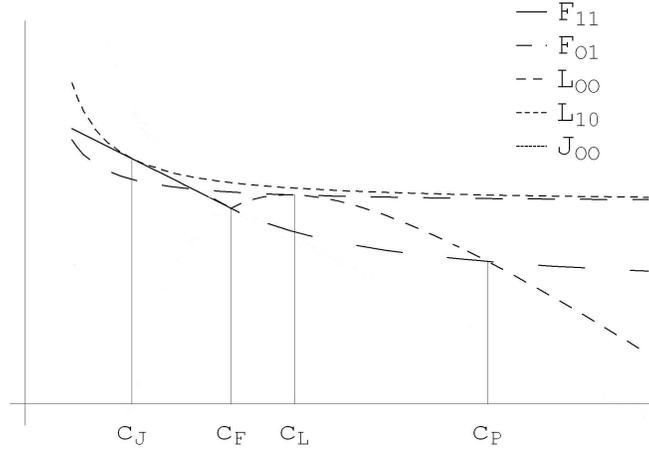
In this case, the convenience of preemption disappears, as long as competitors may coordinate simultaneous investment at the optimal threshold c_J. Nonetheless, investment in T_P and T_F are still reciprocally best responses. Hence, the

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[11]The existence and uniqueness of c_P is proved in Appendix A.

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preemption equilibrium discussed under *Case a* is still an equilibrium, but no longer the only one. Let us define,

$$c_S = max\left(\tilde{c} \,|\, J(c, \tilde{c}) \geq L(c)\right)$$

Recall that the value function that is drawn in Fig.2 is $J(c, c_J)$. In other words, the relevant function $J_{00}(c)$ to the right of c_J is obtained working backwards under the assumption that the threshold is the optimal one. If investment is made at different times, the shape of J_{00} is different from the one shown in the figure. In particular, departing from the optimum will reduce the value of simultaneous investment, so that this may fall below that obtainable with preemption.

In Case b two classes of equilibria exist. There is a preemption equilibrium with the same characteristics discussed under Case a, and a continuum of equilibria for values of the stochastic variable such that $c_J \leq c \leq c_S$. All equilibria may be Pareto-ranked in this case, the optimal choice being simultaneous investment in T_J.

What happens in this case is that the option-like negative value that enters in $L_{10}(c)$ picking up the negative externality associated to the possibility of subsequent entry by the follower, is large enough that the advantage to exploit a larger demand before this happens may not be sufficient to make engaging in preemption profitable relative to waiting and investing simultaneously. As it may be seen in Fig.2, whether the equilibrium is only sequential or also simultaneous depends on the relative position of $L_{00}(c)$ and $J_{00}(c)$. In particular, since for high values of c both curves tend to the same value, the relevant situation will be *Case b* if and only if $K_2 \geq D_2$. This issue will be investigated in more details in the following section.

4 Payment scheme and investment timing

The analysis of the previous section has showed that the determination of times of adoption by competitors may be complicated for at least two reasons. First, in the preemption equilibrium the relevant threshold for the leader's investment is c_P, which cannot be defined in closed form. Second, which thresholds are actually relevant for the timing of adoption depends on whether the equilibrium is sequential or simultaneous. Therefore, once the assumption of exogenous roles is relaxed, the description of the impact of p and r on c_L and c_F provides a very limited contribution to the investigation of the actual times of adoption. In this section, these two effects are studied. Since it has been showed above that even referring just to the pre-commitment thresholds the effect of increases in r are ambiguous, the attention in this section will be mainly on the effects of increases in price, the objective being to check whether the anticipation effect discussed above is robust to endogenous roles.

As to the first issue, the impossibility of finding a closed form solution for c_P

makes the analysis of the impact of the payment scheme on this threshold not straightforward[12].

In order to see what the impact of a change in the payment scheme on the type of equilibrium is, the effect of such changes on the value of the constants D_2 and K_2 needs to be considered. As it may be seen from equations (20) and (19), both the optimal simultaneous threshold c_J and the constant D_2 are independent of price. This is a consequence of what may be considered a specific characteristic of the health care sector, that is the fact that total number of patients is assumed fixed. Since revenues are deterministic and both before and after simultaneous investment each hospital treats exactly half patients, the optimal timing and the value function are independent of p. Therefore, attention may be restricted to the effect on the option value to invest as first (K_2).

In Appendix B it is showed that increases in p may reduce K_2 and hence make the outcome with simultaneous investment comparatively more likely. Since optimal simultaneous investment occurs always later than both the leader's and the follower's in sequential equilibria, by making the simultaneous outcome comparatively more profitable, increases in price may induce providers to delay investment.

The reason why this happens is that from the leader's perspective, the effect of an increase in p is twofold. On the one hand, it increases the additional revenue that may be obtained by investing first, as long as the follower has not invested yet. With exogenous roles, this also induces the leader to anticipate investment. On the other hand, a similar incentive is provided to the follower to reduce the time length of the period characterized by a technological disadvantage. This has a negative impact on the leader's value ($\partial E_2 / \partial p < 0$). If the latter effect outwieghts the former, increases in the price component will lead to a situation where the incentive to preempt the competitor is small enough to make simultaneous investment more convenient.

Recalling the effect of r on pre-commitment thresholds, the following conclusion may be derived from the study of equilibria:

When providers compete over patients, more generous schemes, both in the price and the cost reimbursement component, may delay the adoption of innovative technologies.

5   Welfare Analysis

The aim of this section is to compare the possible outcomes of the strategic investment game as discussed above with the timing an hypothetical social planner would choose, assuming that this may decide, observing the stochastic variable, at what time each hospital should invest. This comparison will then be the base

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[12]It may be checked that not even the implicit function theorem leads to clearcut conclusions. In all the simulations performed in Appendix A increases in p increase the preemption threshold c_P as long as the equilibrium outcome is sequential

for the following attempt to draw some policy implications from the analysis. This issue has apparently been neglected so far in the literature on strategic option games. In several papers, the competitive investment thresholds have been compared with the monopolistic ones, highlighting the erosion of the value of the option to postpone investment implied by strategic interactions. Weeds (2002) compares the strategic solution with the optimal timing under the assumption that competitors may coordinate their investments. Some of the results obtained by Weeds will also be relevant in our analysis. In our case, however, the social planner has not only the ability to coordinate investments, but also a separate objective.

The following social payoff functions are defined respectively for the situations where neither, only one and both hospitals have adopted the innovative technology[13].

$$
\begin{aligned}
W_0 &= B_0 - c_0 \\
W_1 &= x_{10}B_1 + x_{01}B_0 - x_{10}c + x_{01}c_0 \\
W_2 &= B_1 - c
\end{aligned}
\tag{21}
$$

Social welfare is assumed to be given by the total benefit received by patients through treatments received, net of costs of providing the treatment, across providers. The cost of transport is not included in the social welfare function. This may be justified on the ground of a reasonably much greater weight assigned at the social level to health benefits in comparison with transportation costs. In fact, adding this further component would not add much to the analysis[14]. As it is clear from the payoff functions above, it is also assumed that money may be raised to finance payments to providers without any efficiency loss.

From the social perspective, there are now two optimal thresholds to be derived, corresponding to the investment in the first and in the second hospital. In deciding when to invest in the first hospital, the social planner anticipates the option to invest in the second at a later stage. Consequently, there are three value functions, corresponding to the three payoff functions in (21). Following the same approach to the real option problem that was adopted for the private problem the following value functions obtain:

$$
\Omega_2(c) = \frac{B_1}{\rho} - \frac{c}{\rho - \mu} - 2I
\tag{22}
$$

$$
\Omega_1(c) = F_2 c^\beta + \frac{x_{01}B_0 + x_{10}B_1 - c_0 x_{01}}{\rho} - \frac{x_{10}c}{\rho - \mu} - I
\tag{23}
$$

$$
\Omega_0(c) = G_2 c^\beta + \frac{B_0 - c_0}{\rho}
\tag{24}
$$

---

[13]As it is obvious, the situations where hospital A has invested and B has not done so yet is equivalent to its symmetric from the social standpoint.

[14]The main implication of adding transportation costs to the social payoff function is that situations of asymmetric technology become comparatively less desirable, because the overall cost of transport is relatively higher.

with, $\beta < 0$.

Since c is assumed to follow the same stochastic process discussed in the previous sections, the same restrictions also apply. Therefore, the coefficients associated to the terms whose exponential is positive (F_1, G_1) have still to be set equal to zero. The usual value matching and smooth pasting conditions may now be used to determine the optimal investment thresholds and the value of the constants F_2 and G_2. Working backwards, the optimal threshold for the second investment turns out to be:

$$c_2 = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{01}}\right)(x_{01}(B_1 - B_0) + x_{01}c_0 - \rho I) \qquad (25)$$

with, $\beta < 0$.

This expression is not defined when $x_{01} = 0$. This case may be ruled out by introducing the following restriction:

$$\delta < \frac{1}{B_1 - B_0} \qquad (26)$$

In practice, this is not a problem because there always exists a value $x_{01} > 0$ such that it is not optimal to invest in the second hospital, independently of the value of c. Eq. (25) may be used to determine the constant associated to the option value for the second investment:

$$F_2 = \frac{c_2^{1-\beta}}{-\beta}\left(\frac{x_{01}}{\rho - \mu}\right) \qquad (27)$$

The maximum value of the stochastic variable for which it is optimal to adopt technology in the first hospital is:

$$c_1 = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{10}}\right)(x_{10}(B_1 - B_0) + x_{10}c_0 - \rho I) \qquad (28)$$

the value of the second constant being,

$$G_2 = F_2 + \left(\frac{c_1^{1-\beta}}{-\beta}\right)\left(\frac{x_{10}}{\rho - \mu}\right) \qquad (29)$$

The comparison between the competitive and the social optimal solution may start from the analysis of the value functions in the corresponding regions. The structure of the value function is the same, being made up, as long as further investment is possible, of two parts. The linear part in all three functions is just the expected value under the *status quo*, whereas the first term picks up the value of the option to invest at some later stage. The interpretation of the option component, however, is somehow different now. In the competitive case, the option component that was relevant before the first investment (K_2) was given by the algebraic summation of the value of the pure option to invest, net of the option-like term picking up the 'cost' of the threat of entry by the follower (E_2). The possibility of coordinating investments in this case, instead, implies

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a positive value of the opportunity to invest in the second hospital ($F_2 > 0$), after the first has already adopted the innovative technology. This value enters positively the option value for the first investment (G_2), thus picking up the option to expand overall investment, free of competitive pressures.

More generally, there are two separate sources for the differences between the competitive and the social optimal strategies. There is the asymmetry in the objectives pursued on the one hand, and the pure competition effect on the other. A comprehensive interpretation of the differences that arise under different conditions requires these two effects to be disentangled.

The competitive effect may be isolated by comparing the competitive solution with the solution of an hypothetical collusion problem, where, the objective functions being the same, providers may coordinate their investment strategies in order to maximize overall value. This is the analysis Weeds (2002) carries out. That paper provides support for the intuition that competition prevents players from fully exploiting the option to delay investment as long as the outcome is a pre-emption equilibrium. However, when the equilibrium is simultaneous, the investment may be delayed relative to the first-best, at least for the leader.

We can briefly go through the results of a similar exercise for our case in order to isolate the competitive effects in this framework. The optimal thresholds for the collusive case (c_{c1} and c_{c2}) may be easily obtained starting from the social thresholds (equations (28) and (25)), eliminating from the last parenthesis on the right hand side the term including $B_{1,2}$ and dividing ρI by $(1 - r)$:

$$c_{c2} = \left(\frac{\beta}{\beta - 1} \right) \left(\frac{\rho - \mu}{\rho} \right) \left(\frac{1}{x_{01}} \right) \left(x_{01} c_0 - \frac{\rho I}{1 - r} \right) \tag{30}$$

$$c_{c1} = \left(\frac{\beta}{\beta - 1} \right) \left(\frac{\rho - \mu}{\rho} \right) \left(\frac{1}{x_{10}} \right) \left(x_{10} c_0 - \frac{\rho I}{1 - r} \right) \tag{31}$$

It is immediate to check that $c_{c1} > c_{c2}$. Therefore, the social (collusive) optimal investment timing is always sequential in this case. From the assumption that total demand is fixed and the price component is independent of the technology adopted, it follows that the optimal thresholds under collusion, unlike under competition, are independent of p. Since p is multiplied by a positive term both in the expression for c_L and c_F, this provides an incentive toward inefficiently early investment under competition. The weight attached to c_0 is also different. This difference may be interpreted as a kind of externality: while assessing the convenience of investment, each provider will compare future with own current costs, thus failing to account for the reduction in the number of patients treated by the competitor who has not invested yet. When dealing with costs, this leads to overestimation of future costs relative to the social optimum and hence to inefficient delay. Overall, under the condition that ensures non negative profits under the old technology ($p + (1 - r)c_0 \geq 0$), the former effect outweighs the second, thus inducing to anticipate investment.

Finally, the effect of a change in the cost of investment I has to be investigated. The comparison between the thresholds under competition with those under collusion shows that this effect is symmetric for the first investment, but not for

the second. The negative term $-\rho I$ is divided by a smaller number (x_{01}) in the expression for c_{c2} than for c_F. Hence, this adds a new source of inefficiency in the form of "early investment" for the competitive solution. Moreover, the effect being asymmetric across competitors, there will also be an inefficiently short time lag between investments. The intuition for this builds on the observation that the optimal investment decision follows from the comparison between the cost of the investment and the differential in terms of revenues and costs. For the first investment, x_{10} is the number of patients whose cost of treatment depends on the stochastic variable, both in the cooperative and the competitive problem. At the time of the second investment, instead, from the competitor (follower) standpoint the number of patients to treat with the new technology is x_{11}, whereas for the cooperative solution the difference with the previous stage is of x_{01} patients only.

Assuming once more that the optimal competitive thresholds are such that $c_F < c_L$, it can be shown that the optimal thresholds are ranked as follows:

$$c_{c2} \leq c_J \leq c_{c1} \leq c_L$$
$$c_{c2} \leq c_J \leq c_F \leq c_L \tag{32}$$

where, c_J is still the optimal threshold for simultaneous investment.

Only c_{c1} and c_F cannot be unambiguously ranked. Bearing in mind that the stochastic variable enters the payoff function with the opposite sign, these results are perfectly consistent with those from Weeds (2002) in terms of expected time of adoption. It is confirmed, therefore, that under competition the value of the option to delay cannot be fully exploited and this induces inefficiently early investment for both providers, at least as long as the outcome is preemption.

The difference between the 'private' and the social objective, however, plays a role in the opposite direction in our case. The comparison between the collusion (eq. (30) and (31)) and the social thresholds (eq. (25) and (28)) shows that the latter are higher than the former, as a result of the benefits enjoyed by patients entering the social utility function and the fact that profit maximizing hospitals would fail to take some part of the cost of treatment (r) into account. Whether the social thresholds will be larger or smaller than the competitive ones, instead, will depend on the parameter values. As long as the leader's threshold is the highest, one may immediately conclude that the preemption threshold, being by definition higher than the leader's, will exceed any other threshold. When this is not the case, however, the leader's threshold provides just a lower bound for the threshold that is actually relevant in a preemption equilibrium. The problem is again the impossibility to find a closed form solution for c_P. In other words, whereas it follows immediately from $c_L \geq c_1$ that the competitive investment is anticipated relative to the social optimum, the opposite conclusion cannot be drawn if $c_L < c_1$.

This problem, together with the relatively large number of parameters that enters the solution, prevents from achieving a straightforward comparison, similar to that carried out between the competitive and the collusive solution. Bear-

ing this in mind, the following section aims to provide some mainly qualitative policy insights.

5.1 Policy issues

The viewpoint that is adopted in this section is that of a regulator, whose objective is to use the available policy instruments so that the outcome of competition between providers is as close as possible to the first-best. As explained above, a full algebraic analysis is beyond the scope of this section, which provides mainly qualitative insights.

The main instrument available to the regulator is the definition of the payment scheme, and the following analysis will consistently be concentrated on this[15]. The first thing to note looking at the thresholds and the constants that determine which kind of equilibrium will prevail, is that there are different classes of variables playing different roles within the policy analysis. The most meaningful distinction in this framework seems to be that between those that we are going to call 'treatment specific' and 'innovation specific' variables. The elasticity parameter δ (inverse of the cost of transport) is the most relevant in the first class, which also includes the basic technology marginal cost c_0. The innovation specific variables are B_1, μ, σ, I. The first class, unlike the second, is known beforehand, and the policy instruments in principle may be tailored to treatments with different characteristics in this respect. An interpretation of elasticity in terms of urgency has already been provided. Another characteristic of the treatment that may have an impact on elasticity may be the comparison between waiting lists for treatments provided with new *versus* old technology. The restriction on δ that ruled out situations where the demand by a single hospital would exceed one, still holds[16].

Starting from the lowest values of elasticity, in terms of optimal thresholds the situation may be characterized as follows:

When $\delta \to 0$:

- $c_j < c_F < c_L < c_2 < c_1$

- $c_1 \to c_2$

- $c_L \to c_F$

- $c_P \to c_L$

- $c_J \to c_F$

[15]However, it has been seen above that two different classes of equilibria, with specific characteristics in terms of timing of adoption are possible. This result was obtained assuming that providers are perfectly symmetric. Assuming the regulator has the opportunity to give a competitive advantage to one of the players, symmetry would fall and this would have an impact on the adoption timing. Hence, this might be a further policy instrument, whose role might be worth investigating.

[16]As it is clear from inequality (26), this condition also depends on the benefits. Since the following analysis will be carried on for given B_1 and B_0 this issue will be ignored.

The first three points above follow immediately from the equations for the corresponding thresholds. The last two points are in turn implied by these. When $c_L \to c_F$, it is easily proved that $A_2 \to K_2$. Since also the linear parts of F_{01} and L_{00} tend to coincide for $\delta \to 0$, the two curves tend to overlap and the difference between c_P and c_L tends to be canceled.

It is also possible to prove that for very low values of the elasticity, the competitive equilibrium tends to be of preemption, regardless of the values the other parameters assume. Hence, under this extreme condition, the type of competitive equilibrium that prevails is consistent with the social equilibrium, both being sequential. The timing of investment, instead, is not optimal, though the tendency to reduce the time lag between investments for low levels of elasticity is so. Competitive investments both by the leader and the follower will be delayed with respect to the social optimum. This delay will be larger, the larger the difference in the benefits enjoyed by patients treated with alternative technologies, which profit maximizing providers fail to consider[17].

The description of equilibria for $\delta \to 0$ that has just been done holds independently of all the other parameters. As δ is increased, the other variables, including the policy parameters, do play a role both in determining the optimal thresholds and the type of equilibrium. The objective now is to see how elasticity influences the optimal times of adoption in the competitive and the social perspective, given the values of the other variables.

Figure 3:
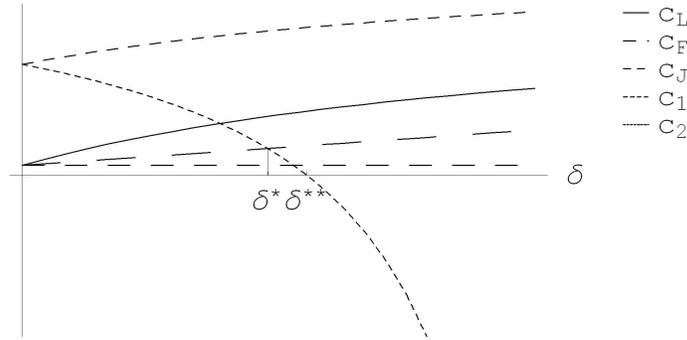
The following results may be proved (see Appendix C):

An increase in elasticity induces an increase in the competitive thresholds both

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[17]Of course, this result may not hold if hospitals were assumed to draw utility directly from benefits enjoyed by patients. However, this section is mainly focused on how differences in treatment specific variables affect the difference between competitive and social optimum. Therefore, we are more interested in changes corresponding to different elasticities rater than in levels.

for the leader and the follower. For the social optimum, instead, the effect is an anticipation of the first investment (higher c_1) and a delay of the second (lower c_2). For $\delta \geq \delta^{**}$ it will always be optimal in the social perspective to adopt the innovative technology in one hospital only.

As it is clear from Fig.3, since both c_F and c_2 are continuous in x_{10}, it follows from what was observed above that there will be a point δ^* such that the threshold associated to the second investment is the same in the social and the competitive solution with sequential equilibrium. For $\delta < \delta^*$ the investment by the follower is inefficiently delayed relative to the social optimum, whereas for $\delta > \delta^*$ it is anticipated.

The level of δ^*, however, depends on the specific characteristics of the innovation. This means that it is not possible for policy purposes to define exactly over which level of elasticity competition induces early investment. The relevant information, though, is the tendency to anticipate the second investment in the competitive situation for treatments that allow patients to be comparatively more responsive to the opportunity of being treated with better technology.

Moving to the analysis of the relevant threshold for the first investment, things get significantly more complicated, due to the impossibility of finding a closed form solution for c_P. The dependency of c_L on the elasticity that appears in the figure provides just a lower bound for actual time of adoption by the leader when the equilibrium involves preemption. In the figure above, the payment parameters p and r are assumed constant. The question now is whether some indication can be given as to the way these parameter should be set in order to reduce the distortions that arise from competition.

We begin from the comparison between c_2 and c_F. It has been shown that for treatments with low elasticity competition tends to induce delayed investment relative to cases where δ is higher[18]. Given the cost of investment I, the comparatively small difference between x_{11} and x_{01} makes it more likely that an increase in r delays the expected time of investment[19]. Since c_F in this region is inefficiently low, the appropriate scheme to reduce the distortion has no cost reimbursement component ($r = 0$)(see also simulations in Appendix C). In terms of price component, however, the payment scheme for low elasticity treatments should be comparatively generous, so that the tendency to delay investment induced by competition may be at least partly counterbalanced. Moving to the first investment, as long as elasticity is low, the curves L_{00} and F_{01}, are relatively close to each other. When this is the case, the difference between c_P and c_F is small. This is coherent with the comparatively small difference between c_1 and c_2 for low values of δ.

As δ gets larger, the optimal threshold for the second investment is reduced. In the competitive situation, this may be induced setting up a less generous scheme for this class of treatments, such that the tendency to increase c_F that

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[18]There will also be delay in absolute terms if, as it has been assumed in Fig.3, the providers' payoff functions do not directly depend on patients' benefits.

[19]Recall from the base model that if $p(x_{11} - x_{01}) - \rho I < 0$, an increase in the cost-reimbursement component r reduces the threshold.

is showed in the figure may be offset. The price component, therefore, should be definitely reduced.

Let us see now how the reimbursement scheme should be designed in order to induce investment by one hospital only, which has been seen to be always optimal from the social perspective for $\delta \geq \delta^{**}$. The level of price that prevents investment by the follower is:

$$p \leq \frac{\rho I - x_{01}c_0(1-r)}{x_{11} - x_{01}} \tag{33}$$

As expected, increases in δ (that imply decreases in x_{01}), must be compensated by lower values of p. As assumed so far, however, the combination of p and r must be such that:

$$p \geq (1-r)c_0$$

The two equations above will only be simultaneously satisfied if:

$$r \geq 1 - \frac{\rho I}{c_0 x_{11}} \tag{34}$$

Inequality (34) implies that when the right hand side is positive, the payment scheme must include a cost-reimbursement component to induce investment by one provider only. The key variable that determines whether this is the case (I) is 'innovation specific'. Furthermore, it should be noted that a necessary condition for c_F to be non positive is $p(x_{11} - x_{01}) - \rho I < 0$. Under this condition, an increase in r reduces the follower's threshold, thus reinforcing the role of a reduction in p in obtaining only one investment. The simulations in Appendix C also seem to suggest that above a certain level of δ and for specific innovations a payment system may be designed that induces the social optimal timing.

The qualitative analysis of how the policy instruments may be used to reduce the distortions that arise from competition may be summarized as follows. The social optimal timing of adoption is always sequential. For treatments characterized by a low responsiveness of patients seeking care to differences in the level of benefit associated to alternative technologies, competitors tend to inefficiently delay time of adoption of innovative technologies. For this class of treatments, a generous pure fixed fee scheme performs comparatively better. As elasticity is increased, the social optimum involves a widening gap between the first and the second investment, up to a point where it becomes optimal to invest in one provider only. The analysis of the effect on the lower bound c_L and the result of the simulations seem to suggest that in the competitive situation, for given c_F, an increase in elasticity induces a higher c_P, consistently with the tendency of the socially optimal timing. In order to rule out investment by the follower when the elasticity parameter is sufficiently large, or sufficiently delay it, adding a cost reimbursement component to the payment scheme *may* be necessary.

6   Conclusions

The paper has investigated the optimal timing of investment in innovative technologies by health care providers competing for patients. This seems a relevant issue within the debate on the increasing costs of health care provision, part of which is usually attributed to the adoption of new technologies that improve the health outcome, but often boost costs.

Particular attention has been paid to the uncertainty that characterizes new technologies especially at the earlier stages of their development. In this context, as it has been recently pointed out also in the health economics literature, the real option approach provides a more comprehensive way to account for uncertainty. The effect of the interaction between the conflicting incentives provided by competition and the option values on the timing of adoption has been studied. As it is typical in game theoretic real option models the equilibrium is either sequential or simultaneous, depending on the parameter values. In the preemption equilibrium, an incentive exists to preempt the competitor up to the point where leader's and follower's values are equaled. In this case investment is sequential in equilibrium. In the second class, besides the preemption equilibrium, a continuum of Pareto-ranked equilibria exists, where investment is simultaneous.

It has been showed that in this framework more generous payment schemes for providers do not always induce to anticipate the adoption of innovative technologies. This happens for the cost-reimbursement component even under precommitment, when the investment does not provide sufficiently large advantages in terms of revenue, given the cost of investment. For the price component, this is a peculiar effect due to the adoption of a real option approach in a competitive setting: there may exist a level of per patient price such that the follower has an incentive to invest early enough to cancel the advantage of the first mover, that will find more profitable to wait for a simultaneous and hence delayed investment.

Depending on the parameter values, investment under competition may happen both later and earlier than the social optimum. The latter case is more likely for treatments for which patients are more willing to move in order to benefit from better technology. It has been showed that the payment system that aims to induce a timing of investment across elasticity levels with the same characteristics as the one an hypothetical social planner would choose, should become less generous as elasticity raises and include no cost reimbursement component for treatments with sufficiently low levels of elasticity.

A   Appendix

Derivation of $F(c)$: In the stopping region, the value function is the summation of the present value of the deterministic part of the payoff function, net of the present expected value of costs, minus the cost of investment. The first

component, of course, is given by,

$$\frac{x_{11}p}{\rho}$$

Following the same steps as in Huisman (2001) (Ch.7, Appendix A1), it may be showed that the expected value of the stochastic component is:

$$\frac{(r-1)x_{11}c}{\rho - \mu} \tag{35}$$

Moving to the *continuation region*, the following Bellman equation applies:

$$\rho F_{01}(c) = V_{01} + lim_{dt \to 0} \frac{1}{dt} E[dF_{01}(c)] \tag{36}$$

Applying Ito's Lemma, the last term on the right hand side may be written as:

$$E[dF_{01}(c)] = \left(\mu c \frac{\partial F(c)}{\partial c} + \frac{1}{2}\sigma^2 c^2 \frac{\partial^2 F(c)}{\partial^2 c} \right) dt + \circ(dt) \tag{37}$$

The substitution of this into eq. (36) yields the following differential equation:

$$-\rho F_{01}(c) + \mu c \frac{\partial F(c}{\partial c} + \frac{1}{2}\sigma^2 c^2 + V_{01} = 0 \tag{38}$$

The general solution is:

$$F_{01}(c) = A_1 c^{\beta_1} + A_2 c^{\beta_2} + \frac{x_{01}p + (r-1)x_{01}c_0}{\rho} \tag{39}$$

where, $\beta_1 > 1$ and $\beta_2 < 0$ are the solutions of the following equation:

$$\frac{1}{2}\sigma^2 \beta^2 + \left(\mu - \frac{1}{2}\sigma^2 \right)\beta - \rho = 0 \tag{40}$$

For sufficiently large values of c it will not be profitable to exercise the option to invest. Hence the follower's value in this case is,

$$\frac{x_{01}p + (r-1)x_{01}c_0}{\rho}$$

This adds a restriction on the general solution (39), which requires A_1 to be set equal to zero.

Derivation of $L(c)$: Also in this case, the value function is obtained working backwards. In the follower's stopping region, the value for the two perfectly symmetric providers is obviously identical ($F_{11}(c) \equiv L_{11}(c)$). For the leader, however, there will be three relevant functional forms corresponding to the ranges of values for which it is optimal for the leader to wait, the leader only

has invested, both have invested. The relevant *Bellman equation* in the second region is:

$$\rho\left(L_{10}(c) + I\right) = V_{10} + lim_{dt \to 0} \frac{1}{dt} E[dL_{10}(c)] \tag{41}$$

Using Ito's Lemma as it has been done above for the follower's case, a differential equation is obtained, with the following general solution:

$$L_{10}(c) = E_1 c^{\beta_1} + E_2 c^{\beta_2} + \frac{x_{10}p}{\rho} + \frac{(r-1)x_{10}c}{\rho - \mu} - I \tag{42}$$

Since, as for the follower, the stochastic variable is a negative component of the payoff function, the coefficient corresponding to the positive exponential (E_1) must again be set equal to zero. Of course, again the two functions should match at the follower's threshold:

$$L_{10}(c_F) \equiv L_{11}(c_F)$$

This time, however, the investment decision is up to the follower. Hence, no smooth pasting condition is required to hold at that point.

The leader's value function in the continuation region $(L_{00}(c))$ may be obtained by straightforward adaptation of the steps followed to obtain $F_{01}(c)$:

$$L_{00}(c) = K_2 c^\beta + \frac{x_{00}p}{\rho} + \frac{(r-1)x_{00}c_0}{\rho}$$

Finally, *value matching* and *smooth pasting* conditions are used to determine the value of K_2 and the threshold c_L.

Derivation of $J(c)$: Since the assumption in this case is that the providers may coordinate simultaneous investment at the optimal threshold c_J, technically speaking, the problem is one of monopoly. Using the payoff functions V_{11} and V_{00} respectively in the stopping and the continuation region, the same process as for the follower's problem may be applied to derive the value function in (18).

Condition that ensures $c_L > c_F$: Under the following condition, the leader's threshold is larger than the follower's threshold and therefore 'cascades' are ruled out:

$$\rho I > p(x_{10} - x_{00}) + (1 - r)c_0 \left[\frac{x_{00}x_{11} - x_{10}x_{01}}{x_{11} - x_{10}} \right] \tag{43}$$

The first term on the right hand side is clearly positive, whereas the second is negative. It should be observed that a more generous scheme, either on the price or cost reimbursement component, makes the 'cascade' comparatively more likely.

Proof that there exists a unique $c_P > c_L$: It is immediate to see from the value functions, that for c large enough it will be $L_{10}(c) \leq F_{01}(c)$. Since,

$$F'_{01}(c) < 0 \quad \forall c(t)$$
$$F''_{01}(c) > 0 \quad \forall c(t)$$
$$L''_{10}(c) < 0 \quad \forall c(t)$$

the existence and uniqueness of c_P if immediately proved if $L_{10}(c_L) > F_{01}(c_L)$. By construction (value matchng condition in $c(F)$ for the leader) there will be at least an intersection between $L_{10}(c)$ and $F_{01}(c)$. Since we have ruled out situations where $c_F \geq c_L$, and L_{10} is concave for all values of c, there will be two intersections. The lower value at which the curves intersect is c_F. In c_L, $L_{10}(c)$ and $L_{00}(c)$ are tangent. Observing that for sufficiently large values of c, $L_{00}(c)$ lays above $F_{01}(c)$, there may be two cases. If $L_{00}(c)$ is always higher than F_{01}, it is immediately proved that $L(c_L) > F(c_L)$. If this does not hold, $L_{00}(c)$ is flatter than $F_{01}(c)$ and in principle c_L might lay in the region where $L_{10}(c) < F_{01}(c)$. Since $L''_{10} < 0$, then it will be $L'_{10}(c_F) > L'_{10}(c_L)$. But in this case we have $L'_{00}(c) > F'_{01}(c) \forall c$ (smaller in absolute value), and therefore the tangency between $L_{10}(c)$ and $L_{00}(c)$ occurs in the region where $L_{10}(c) > F_{01}(c)$.

B   Appendix

The effect of p on optimal thresholds and equilibrium outcomes:

Let us start considering the effect on K_2 of increases in p. The less intuitive and hence most interesting case is that where $\partial K_2 / \partial p < 0$. This will be the case if the following condition is satisfied:

$$-\beta p c_F^{-\beta-1} \left(\frac{\beta}{\beta-1} \right) \left(\frac{\rho-\mu}{\rho} \right) \left(\frac{1}{x_{11}} \right) \left(\frac{x_{11}-x_{01}}{1-r} \right) + c_F^{-\beta} \geq -\frac{\beta}{x_{11}} c_F^{-\beta}(x_{11}-x_{01}) + c_L^{-\beta}$$

All the terms in the expression are positive. It may be showed that the first term on the left hand side is always larger than the first term on the right hand side. Of course, instead, $c_F^{-\beta}$ is smaller than $c_L^{-\beta}$. A priori, then, it is not possible to conclude that either side is larger. Attempts to go on with the algebraic manipulation get soon rather cumbersome. It may be observed, however, that the situations where the difference between c_L and c_F is large are the main candidates for the inequality not to be satisfied. This happens, *ceteris paribus*, for comparatively low levels of p. This follows from observing that an increase in p has a larger effect on c_F than on c_L. The following simulations, however, show that even for prices that weakly satisfy the non-negative profit condition, $\partial K_2 / \partial p$ may be negative.

Two simulations are run for different sets of reasonable parameters, letting p

increase, starting from the minimum value such that $p \geq (1-r)c_0$.

Simulation 1:
Fixed parameters:
$r = 0.3$; $c_0 = 4$; $\rho = 0.05$; $I = 20$; $\mu = -0.05$; $\sigma = 0.08$; $B_1 = 6$; $B_0 = 2$; $\delta = 0.2$.

Tab.1

p	c_F	c_J	c_P [20]	D_2	K_2	Equilibrium
2.8	1.08	1.08	3.58	4.52	12.73	Case a
3.2	1.51	1.08	4.05	4.52	9.57	Case a
3.6	1.94	1.08	4.59	4.52	5.81	Case a
4	2.37	1.08	5.15	4.52	1.44	Case b
4.4	2.8	1.08	5.63	4.52	-3.54	Case b

Simulation 2:
Fixed parameters:
$r = 0$; $c_0 = 2$; $\rho = 0.04$; $I = 15$; $\mu = -0.03$; $\sigma = 0.15$; $B_1 = 5$; $B_0 = 3$; $\delta = 0.2$.

Tab.2

p	c_F	c_J	c_P	D_2	K_2	Equilibrium
2	0.62	0.62	1.19	3.81	4.2	Case a
2.4	0.74	0.62	1.43	3.81	4.49	Case a
2.8	0.87	0.62	1.65	3.81	3.74	Case b
3.2	0.99	0.62	1.89	3.81	3.12	Case b
3.6	1.12	0.62	2.18	3.81	2.34	Case b

The simulations show that, as the price increases, not only the pre-commitment thresholds (the follower's is still relevant also in preemption equilibria), but also the preemption threshold seems to increase. In both cases, for low values of p the equilibrium is of preemption (*Case a*). As p increases, K_2 is reduced and falls below D_2 for sufficiently generous payments. When this happens, the Pareto-superior equilibrium is simultaneous and the corresponding threshold is c_J, which determines a sort of jump corresponding to a significant delay of adoption.

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[20]The values of c_P that are reported in this and in the following tables are approximated.

C Appendix

Effects of elasticity on optimal thresholds: Recalling that increases in δ are reflected in increases (reductions) in x_{10} (x_{01}), it is easy to check that a higher level of δ increases the social threshold c_1 and reduces c_2.

For the competitive thresholds c_F and c_L, the proof follows immediately from the derivatives with respect to δ:

$$\frac{\partial c_L}{\partial \delta} = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{10}^2}\right)\left(\frac{\partial x_{10}}{\partial \delta}\right)\left(\frac{px_{00} + \rho I}{1 - r} - x_{00}c_0\right)$$

$$\frac{\partial c_F}{\partial \delta} = \left(\frac{\beta}{\beta - 1}\right)\left(\frac{\rho - \mu}{\rho}\right)\left(\frac{1}{x_{11}}\right)\left(\frac{\partial x_{10}}{\partial \delta}\right)\left(\frac{p}{1 - r} - c_0\right)$$

Both derivatives are positive (strictly in the first case) under the non negative profit condition.

Simulations: The simulation in Tab.3 is aimed at visualizing the effects of the different degrees of elasticity on the investment thresholds and the type of equilibrium outcome, given the other parameter values. It is build starting from *Simulation 2* above (Tab.2), setting price at an intermediate level ($p = 2.8$) and keeping all the other parameters unchanged.

Tab.3

δ	x_{10}	c_F	c_J	c_P	c_2	c_1	D_2	K_2	Equilibrium
0.01	0.51	0.63	0.62	0.7	2.15	2.19	3.8	3.81	Case a
0.13	0.63	0.78	0.62	1.39	1.84	2.36	3.8	3.84	Case a
0.24	0.74	0.92	0.62	1.8	1.31	2.47	3.8	3.61	Case b
0.36	0.86	1.06	0.62	2.03	< 0	2.56	3.8	2.94	Case b
0.48	0.98	1.22	0.62	2.21	< 0	2.63	3.8	1.85	Case b

Tab.3 shows that the effect of δ on c_p seems consistent with what we expected observing the effect on its lower bound c_L. Therefore, in preemption equilibria the leader tends to invest earlier when this enables to attract a relatively large number of patients, other things being equal. It is also worth observing from the last column that as δ increases there may be a shift from sequential to simultaneous equilibria. This effect will be more carefully discussed in the following simulation.

Given that some effects are particularly difficult to investigate algebraically, we investigate in a new simulation how the characteristics of the social optimal timing for treatments with different characteristics in terms of elasticity may be ensured by appropriately designing the payment scheme. As it has been seen above, innovation specific characteristics, that are kept constant in the simulation do play a role. However, the qualitative insights associated to the effects of changes in the treatment specific parameter, seem to be valid independent of the values the other parameters take on.

Tab.4

δ	x_{10}	p	r	c_F	c_J	c_P	c_2	c_1	D_2	K_2	Equilibrium
0.01	0.51	3.1	0	0.64	0.62	0.76	2.15	2.19	3.8	3.81	Case a
0.13	0.63	2.8	0	0.78	0.62	1.18	1.84	2.36	3.8	3.84	Case a
0.24	0.74	2.6	0	1.07	0.62	1.64	1.31	2.47	3.8	3.98	Case a
0.36	0.86	1.5	0.5	< 0	< 0	2.52	< 0	2.56	0	5.09	Case a
0.48	0.98	1.4	0.5	< 0	< 0	2.62	< 0	2.63	0	7.35	Case a

Let us start using the parameter values as fixed in Tab.2 and Tab.3 and let δ vary. Starting from a very low value of δ, if p is left at the same level as in Tab.3 the equilibrium is sequential but, as expected, both the leader's and the follower's investment turn out to be delayed in comparison with the social optimum. Therefore, the aim should be to keep the same type of equilibrium (sequential) but increase thresholds. It may be checked that for the values of the first row of Tab.4, we are in the situation where increases in r induce to delay investment. Therefore, it is confirmed that in order to approach the social optimal timing it is optimal to set $r = 0$. Starting from the benchmark in Tab.3, then, what we may try to do is to increase price for $\delta = 0.01$. The best one can do turns out to be setting $p = 3.1$. The limit to the increase in this case is connected to the effect on K_2. If p is raised above that level, then K_2 falls below D_2 and the equilibrium becomes simultaneous. As it may be observed, the effect on the thresholds of raising p from 2.8 to 3.1 is almost negligible. In fact, as it is intuitive, when the elasticity is very low, the possibility to impact on the timing is also limited, simply because the advantage in terms of additional patients obtainable by investing in the new technology is small. Hence, even setting $p = 3.1$ and $r = 0$, c_P is lower than c_1 and c_F is lower than c_2. The message seems to be that the best payment scheme for low elasticity treatments is completely prospective, but even so providers tend to invest later than it would be socially desirable.

After the first increase of delta (second row), the objective is still to raise the competitive thresholds, which are lower than the respective social optimal for given values of the other parameters. If for the new value of the elasticity the price were kept equal to 3.1, we would end up again in a simultaneous equilibrium. The highest price that ensures a sequential equilibrium is $p = 2.8$. The situation, though, is still one where increases in r would reduce the threshold. Therefore, r is again set equal to zero. Even so, however, the competitive thresholds are still lower than the social ones. However, the gaps $c_1 - c_P$ and $c_2 - c_F$ are reduced in comparison with the first row, and hence the timing of investment may be considered somehow closer to the social optimum.

For $\delta = 0.24$, if all the other parameter values are left unchanged, c_P and c_F are still respectively lower than c_1 and c_2 and the equilibrium becomes simultaneous, which implies a delayed investment, that is the opposite of what we are looking for. By reducing p to a level such that the equilibrium is again sequential, we end up again in a situation where the objective to anticipate the

investment requires to set $r = 0$. The highest value of p that allows a sequential equilibrium is $p = 2.6$.

The following increase in delta ($\delta = 0.36$) leads to a situation where it would be socially optimal to have investment by one provider only. Hence, the aim is to set up a payment scheme that ensures this characteristic and induces investment by the leader as close as possible to the first investment in the social perspective. Let us start assuming that r may be kept equal to zero. It is easily checked that setting p equal to the lowest value such that $p \geq (1 - r)c_0$, the follower has still an incentive to invest. In the simulation, at this point we are in a situation where increasing r would increase the threshold. What we try to do then is to reduce p further in order to reach the situation where this is not the case. At this point, we need to increase r in order to satisfy the non negative profit condition. But now, this will further reduce the follower's threshold. Setting $p = 1.5$ and $r = 0.5$, we induce no investment by the follower and a threshold for the leader that is surprisingly close to the social optimum. Since in this case the optimal simultaneous threshold is also negative, and therefore $D_2 = 0$, whereas K_2 is positive, there actually exists an incentive to preemption. Therefore, it is checked that the equilibrium is also sequential.

In the last row, r is left unchanged. The increase in elasticity allows a further reduction in p. Again, the preemption threshold is quite close to the social optimum.

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