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Keywords: Health Care, Investments

JEL Classification: I18, D92

R. Levaggi and P. Pertile acknowledge the support from the Italian Ministry of Education (PRIN programme 2007/2008). Earlier versions of the paper have been presented at the 10th PET Conference in Istanbul, the 8th ECHE in Helsinki, the 2nd NERI meeting in Padova and at the University of Augsburg. We would like to thank the participants and in particular Mathias Kifmann and Robert Nuscheler and for helpful comments. The usual disclaimer applies.

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Static and Dynamic Efficiency of Irreversible Health Care Investments under Alternative Payment Rules*

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Abstract

The paper studies the incentive for providers to invest in new health care technologies under alternative payment systems, when the patients' benefits are uncertain. If the reimbursement by the purchaser includes both a variable (per patient) and a lump-sum component, efficiency can be ensured both in the timing of adoption (dynamic) and the intensity of use of the technology (static). If the second instrument is unavailable, a trade-off may emerge between static and dynamic efficiency. In this context, we also discuss how the regulator could use the control of the level of uncertainty faced by the provider as an instrument to mitigate the trade-off between static and dynamic efficiency. Finally, the model is calibrated to study a specific technology.

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1 Introduction

Since quasi-markets started to spread across health care systems, health economists have focused on the characteristics of the payment schemes, as a crucial point in the contractual relationship between the purchaser and the provider. Several peculiarities of the health care market have been highlighted and their implications for the definition of (second-best) efficient contracts investigated[1].

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1See for example Chalkley and Malcomson (1998, 2000)

One characteristic of the treatment provided to patients whose impact on the efficiency properties of alternative reimbursement schemes seems to have been largely neglected so far is that often the provision of innovative treatments is the result of an irreversible investment decision. The most obvious example is the investment in equipment whose cost is sunk, at least to some extent. However, there may be several other less obvious forms of irreversibility. For example, Griffin et al. (forthcoming) show that even when a new technology is such that the decision to admit it to reimbursement is not formally irreversible (e.g. pharmaceuticals, medical devices), it may involve some degree of irreversibility if the decision weakens the incentive to accumulate new evidence on the actual (cost-)effectiveness of the new technology.
Although some efforts have been made to interpret the empirical evidence concerning the diffusion of new technologies and the effect on the outcome of hospital care[2], the literature has not yet contributed to a full understanding of how regulation should be used to ensure that adoption and use decisions of new health technologies are "good value (health) for money" over time. A contribution to the static dimension of the problem has been recently provided by Barros and Martinez-Giralt (2009), but the dynamic dimension is still almost unexplored, despite the awareness of its importance [3]. This rather scant interest is in sharp contrast with the concern that technological innovation is a major health care cost driver (Weisbrod, 1988) and that uncertainty on the performance of new technologies is often substantial at the outset (Gelijns and Rosenberg, 1994; McClellan, 1995). A further motivation to investigate this issue comes from the variety of solutions adopted in different health care systems for the reimbursement of capital costs (HOPE, 2006). For instance, in a number of European countries (Austria, Finland, France, Italy, Sweden, The Netherlands) tariffs tend to include these costs, whereas in others they may be separately reimbursed (Denmark, Germany, Portugal, Spain).
The adoption of a new technology with the characteristics of an irreversible investment is an intrinsically dynamic problem, the study of which requires to depart from the structure of the static models mainly employed so far to study the purchaser-provider relationship. Our approach is based on the literature on investment under uncertainty (Dixit and Pindyck, 1994). This enables us to investigate two dimensions of efficiency for alternative payment schemes: the static dimension concerning the provision of the treatment to those patients for whom benefits exceed costs, and the dynamic efficiency concerning the optimal adoption timing for a technology whose benefits are still uncertain.
We show that both static and dynamic efficiency are attainable if the purchaser makes, on top of a fixed fee per patient, a lump-sum payment to cover part of the capital cost. If the payment is simply based on the fixed price component, a trade-off may emerge between static and dynamic efficiency: the price that ensures that the efficient number of patients is treated provides a weak

[2] See, among others, Bokhari (2009); Baker and Phibss (2002).

[3] *"..., I will contend that economists have been too preoccupied with a one-period model of health care services that takes technology as given, and that we need to pay more attention to technological change."(Newhouse, 1992, p. 5).*

incentive to invest, so that the adoption of the new technology will be delayed in comparison with the social optimum. The reimbursement systems adopted in several countries do not involve any lump-sum payment at all. This may be due to either liability constraints for the purchaser or inability to differentiate the pricing rules for technologies with substantial capital costs. Whatever the reasons leading to this choice, our model shows that this payment system produces a regulatory failure. Given the constraints that seem to characterize the implementation of immediate capital cost reimbursements, we lastly discuss use by the regulator of control of the uncertainty faced by the provider as an instrument to mitigate the trade-off between static and dynamic efficiency.
The paper is organized as follows. Section 2 introduces a simple version of the model that yields closed-form solutions. These are obtained and discussed in the following Section. A generalization of the model is presented in Section 4, whereas Section 5 discusses the policy implications. Section 6 presents a calibration of the model for a specific technology, which leads to the description of a second-best efficient policy and to a tentative measure of the cost of a regulatory failure for that case. Section 7 concludes.

2 The Base Model

2.1 The Environment

A new medical technology is available in the market and it requires an instantaneous sunk cost[4], I, to be adopted. To simplify the analysis, and to obtain closed form solutions that help the intuition of how the payment rule influences the provider's behavior, in this section we assume a linear form for the instantaneous benefit function[5]:

$$b(x_t, \mu_t) = a + \mu_t x_t \tag{1}$$

where x_t is the number of patients treated in the period, and μ_t is a measure of effectiveness. Underlying eq. (1) is the assumption that all patients receive the same benefit from the treatment[6].
The constant a represents the net benefit accruing to society as a consequence of the technology adoption, irrespective of the number of patients treated. It can be interpreted as the net effect of informative spillovers, an impact on relational quality, and the impact on the efficiency of other providers which patients could choose. The first aspect relates to the impure public good aspect of the new technology. Health care technologies produce a benefit to all the individuals in terms of an option value to use it in case of need. A new treatment is available

[4]The decision that we study may be indifferently seen as the one of adopting the technology to treat patients who were previously not treated, or to replace a standard technology with a new one. In this case, the net benefits of the former are normalized to zero.

[5]As will be shown in Section 4, the quality of the results obtained under this assumption are robust to the choice of more general benefit functions.

[6]This could be the case for some rather basic technologies, as well as highly specific technologies.

and this positively affects the utility of each individual as a potential patient. The second aspect relates to the positive effect that the new technology has on the intrinsic motivation of the medical staff. The benefit accruing to the patients depends on the quality of the treatment which in turn depends on the technological content of the health care (medical quality) and on the effort of the medical staff in motivating the patient to comply with the therapy (relational quality). A recent literature [7] allows the physicians' utility function to depend also on the health outcome and the technology content of the productive process adopted by the hospital. In this case, the introduction of the new technology increases the effort of the medical staff in terms of relational quality, which in turn improves the benefit that patients receive from the treatment. Unlike the first two factors affecting the parameter a, the effect of a new adoption on the efficiency of provision of the treatment by other providers may be negative in strongly competitive contexts. In this case, competition may create an incentive to adoptions in excess of the efficient level, thus reducing the overall level of efficiency of provision[8].

Since the technology is innovative, there is uncertainty on the benefits that it can actually provide to patients. In particular, we assume that μ follows a trendless geometric Brownian motion[9]:

$$d\mu_t = \sigma \mu dw_t$$

where dw_t are identically and independently distributed according to a normal distribution with mean zero and variance dt, and the volatility parameter σ is constant. The stochastic process represents uncertainty on the evolution of the performance of the new technology. For the sake of simplicity, we assume that uncertainty is restricted to the period before the adoption. Once the investment is made, the technology characteristics are fixed at the level corresponding to the time of adoption[10].

The cost function for the base model is:

$$c(x_t) = \frac{1}{2} x_t^2 \tag{2}$$

For the sake of simplicity, we work with an infinite time horizon. The model requires identification of a component of the investment cost I, which is equally

[7] See Levaggi et al. (2009) and references therein.

[8] This is referred to as "medical arms race" in the literature (Robinson and Luft, 1985). For a discussion of the impact of competition on the timing of investment in new health care technologies under uncertainty, see Pertile (2008).

[9] This means that no deterministic change in effectiveness over time is assumed. Positive drift parameters could be interpreted as reflecting the expectation that on average the technology will go through a development process that leads to improvement in its performance. None of the results that we obtain rely on this assumption.

[10] The situation where uncertainty stops once the technology has been adopted is consistent, for example, with cases where it is related to the characteristics of the technology. In this case, once a certain version of the technology is adopted, uncertainty disappears. Uncertainty may not be resolved after the investment when it is due to limited evidence or the evolution of the cost of materials - consumables or pharmaceuticals - necessary for the treatment.

attributed to each period. Given the infinite time horizon, this is ρI. With no loss of generality we also assume that there are no fixed costs, other than the cost of investment.

2.2 The Purchaser

We assume that the purchaser maximizes total welfare over time. The corresponding instantaneous payoff function is,

$$\Pi_t^{pu} = b(x_t, \mu_t) - c(x_t) \tag{3}$$

In our model the purchaser has the same role as an external regulator that has to define the payment rule for a number of purchasers and providers, aiming to maximize total welfare. Without loss of generality we assume that the purchaser sets the rules. We also assume that the purchaser can commit to the rule announced. The purchaser sets the payment rule and defines a level of effectiveness below which providers are not allowed to adopt the new technology. In particular, we assume that there are two parameters which contribute to the definition of the payment rule: the fixed-fee which is paid for each treatment provided, and a lump-sum contribution to investment costs, i.e. a sum that the purchaser pays to the provider at the time of adoption, as a contribution to capital costs. In spite of the present debate (Claxton et al., 2008), reimbursement schemes designed in different health care systems are more or less strictly cost based. We partially follow this approach by separating the price paid to the provider for each treatment into two components. The first one is meant to reimburse the marginal cost of the treatment provided, whereas the second is a reimbursement of the capital cost component of the technology. The marginal cost reimbursed may be different from the true marginal cost incurred by the provider. In fact it represents the cost to treat the patient for whom the marginal cost is equal to the marginal benefit μ. In this respect our formula, although cost based, also takes also account of the value of care produced. The nature of the second component is such that its size will necessarily depend on the number of patients treated. In particular, it will be greater the smaller the number of patients treated. Moreover, given the form of the cost function, the marginal cost component also depends on that variable.
The structure of the payment rule is the following:

$$P_t = \begin{cases} p_t x_t + \gamma I & \text{for } t = t_A \\ p_t x_t & \text{for } t > t_A \end{cases}$$

where t_A denotes the time of adoption of the new technology by the provider. In that period, the purchaser may decide to make a lump-sum payment γ ($0 \leq \gamma \leq 1$) that reduces the cost of investment actually faced by the provider. In all periods in which the technology is in operation ($t > t_A$), the purchaser pays a price for each patient treated:

$$p_t = c_x(x_t^s) + \frac{\lambda \rho I}{x_t^s} \tag{4}$$

where it is assumed that in setting the price level the purchaser refers to the number of patients which is optimal from his standpoint (x^s). The price is made up of two components. The first is the marginal cost of the treatment, which is always covered by the price. The parameter λ ($0 \leq \lambda \leq 1$) captures an additional component, which reflects the part of fixed costs reimbursed through the price.
Since the number of patients that ensures equality between marginal costs and marginal benefits is $x_t^s = \mu_t$, the price function for any period subsequent to the adoption can be written as:

$$p_t = \mu_t + \frac{\lambda \rho I}{\mu_t} \tag{5}$$

When the technology is adopted, the purchaser observes the value of μ and sets the price according to the rule in eq. (5). The payments made at the time of adoption (if any) and in subsequent periods also depend on γ and λ to which the purchaser had previously committed. Given our assumption that uncertainty ceases after the adoption, the price is constant for any subsequent period.
For very low values of μ this price formula could provide perverse incentives implying increasing reimbursement prices as effectiveness falls. In real life, the adoption of a technology with very low effectiveness will simply not be an issue because there are typically authorities that would prevent the admission of these technologies into the market[11]. We assume that the purchaser fixes a minimum level of effectiveness below which adoptions are not allowed[12]:

$$\underline{\mu} = \sqrt{\lambda \rho I} \tag{6}$$

This ensures that the price in eq. (5) is a non-decreasing function of μ. Unless explicitly stated, in the rest of the paper we deal with the case where $\mu \geq \underline{\mu}$.

2.3 The Provider

We assume that the provider's instantaneous payoff function is the difference between revenues and costs of provision:

$$\Pi_t^{pr} = \left[\mu_t + \frac{\lambda \rho I}{\mu_t}\right] x_t - c(x_t) \tag{7}$$

The provider decides when to adopt the new technology, in order to maximize its payoff function over time. Although we also study the case where the purchaser can enforce the desired number of treatments per period, we are mainly

[11] It is well known that in some health care systems, this rule is more or less explicitly formalized. For example, the rule could take the form of a maximum value of the *Incremental Cost-Effectiveness Ratio (ICER)*.

[12] We could alternatively assume that below that level of effectiveness the provider can adopt the technology, but the reimbursement per patient is $p = 0$. The result would be identical because in both cases the provider never invests.

interested in the situation where the provider is free to decide it. This is a very relevant point in the current debate on the appropriateness in the use of health care technologies. When the provider is free to set the number of treatments, the definition of the payment rule affects the provider's payoff and hence the investment decision both directly, due to the change in the price per patient and the actual cost of investment, and indirectly, by changing the optimal number of treatments from the provider's perspective.

3 Optimal statics and dynamics

3.1 The first best

In order to set a benchmark, we study the solution that ensures that the difference between the benefits for patients from treatments provided and the costs of the technology (adoption and operation) are maximized. Given the characteristics of the purchaser's payoff function defined above, the first best solution also coincides with the case where the purchaser decides both the timing of adoption and the number of patients treated in each period. The solution to this problem requires maximization of total welfare over time (eq. 3), also taking the investment cost I into account.
To characterize such solution we define the following dimensions of efficiency:

- *Static*: efficiency in the provision of the treatment, once the technology is adopted. If the provision is efficient, only patients for whom the marginal benefit is at least as large as the marginal cost are treated. This requirement is satisfied when $x_t^s = \mu_t$.

- *Dynamic*: efficiency in the timing of adoption of the new technology. The benchmark for this efficiency dimension is given by a threshold value of the stochastic variable that should trigger investment once hit, whereas waiting is the dynamically optimal strategy for lower values.

The following proposition defines the optimal investment threshold for the first-best.

Proposition 1 *In the first best, dynamic efficiency is characterized by the following optimal threshold:*

$$\mu_{pu}^* = +\sqrt{\left(\frac{2\beta}{\beta - 2}\right)(-a + \rho I)} \tag{8}$$

β in eq. (1) is the the positive root of the following equation:

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

It can be checked that $\beta > 1$ and that β is inversely related to the level of uncertainty σ.
Proof:
Substituting the efficient number of patients into eq. (3), the following instantaneous payoff function is obtained:

$$\Pi_t^s = \frac{\mu_t^2}{2} + a \tag{10}$$

The type of problem to solve is referred to as "optimal stopping" in the real option literature (Dixit and Pindyck, 1994, chap.4). The idea is that at any point in time the value of immediate investment (*stopping*) is compared with the expected value of waiting dt (*continuation*), given the information available at that point in time (the value of the stochastic variable) and the knowledge of the process. The value of the investment may be written as,

$$V^{pu}(\mu_t, t) = max\left[\Omega^{pu}(\mu_t, t), \frac{1}{1+\rho dt} E\left[V^{pu}(\mu_t + d\mu_t, t+dt)|\mu_t\right]\right]$$

where $\Omega^{pu}(\mu_t, t)$ is the expected value of investing at time t, when the stochastic variable is equal to μ_t. For the sake of simplicity the project time horizon as well as the option life are assumed infinite.
V^{pu} may be interpreted as the value of the opportunity to invest in the new technology, which is the maximum between the expected values of "killing" the option to invest immediately, and waiting dt, thus keeping the option alive.
The optimal threshold may be obtained using dynamic programming (Dixit and Pindyck, 1994). Let's start from the definition of the value function after the investment has been made:

$$\Omega^{pu}(\mu_t) = \frac{1}{\rho}\left(\frac{\mu_t^2}{2} + a\right) - I$$

Before the investment is made, the project's value corresponds to the opportunity to make the investment. This value may be written as $Z\mu_t^\beta$ (see Appendix).
We can now write the purchaser's value function in compact form:

$$V^{pu}(\mu_t) = \begin{cases} Z\mu_t^\beta & \text{for } \mu_t < \mu_{pu}^* \\ \frac{1}{\rho}\left(\frac{\mu_t^2}{2} + a\right) - I & \text{for } \mu_t \geq \mu_{pu}^* \end{cases} \tag{11}$$

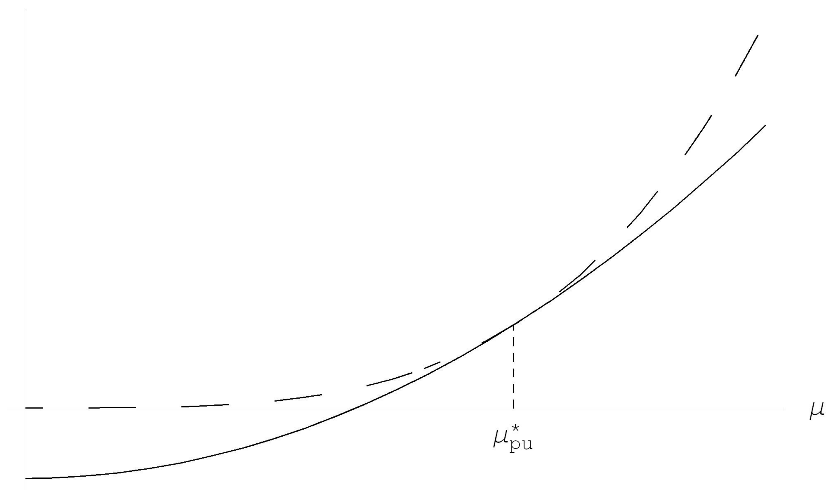
where μ_{pu}^* is the threshold that characterizes the optimal timing of investment. The values of μ_{pu}^* and Z are simultaneously determined imposing appropriate boundary conditions on the value function. The typical boundary conditions for these problems are the so-called *value matching* and *smooth pasting* conditions. The former ensures that the value function is continuous between the waiting and stopping region, i.e. at the threshold. The latter also requires the derivatives w.r.t. μ to be equal at that point. Hence,

$$Z = \frac{(\mu_{pu}^*)^{2-\beta}}{\rho\beta}$$

The substitution of this value into the *value matching* condition yields the value of the threshold in eq. (8). *Q.E.D.*

Figure 1 illustrates the value functions incorporating the optimal decision. The dashed line is the value of waiting (first line in eq. 11), or the value of the opportunity to invest. Since the dynamic approach to the solution of the problem

Figure 1: First Best Value Functions



recognizes that there is an opportunity but no obligation to invest, this value is non-negative also for low values of μ, when the NPV (solid line), i.e. the value of investing for a given value of μ, is negative. The threshold (μ^*_{pu}) is obtained by imposing appropriate boundary conditions on the two functions in eq. (11): *value matching* requires the value of waiting to equal the value of investing at the threshold, *smooth pasting* requires their derivatives to be the same at that point. Since it is optimal to invest for values of the threshold at least as large as the threshold, above this the value of investing (second line in eq. 11) becomes the relevant component of the value function. When the existence of an option to postpone the investment is taken into account, the optimal threshold exceeds the one corresponding to the NPV criterion (intersection between the solid line and the horizontal axis). This difference is larger the greater the uncertainty.
The level of the optimal threshold is inversely related to the expected time of investment. Eq. (8) shows that unless a is very big ($a \geq \rho I$)[13] a positive threshold exists only if $\beta > 2$. Since $\frac{d\beta}{d\sigma} < 0$, this means that if uncertainty exceeds a certain level it is not optimal from the societal perspective to adopt the new technology for any value of μ.[14]

[13] Obviously if a is very big, the level of benefits is so high that from the societal perspective it is optimal to adopt the new technology immediately and independently of the value of μ.

[14] Usually, very large levels of uncertainty may be observed at a stage where the adoption of the technology is not permitted yet. For instance, Sculpher and Claxton(2005) use a log-normal distribution to evaluate the health (utility) gain per 10 Kg weight loss due to the adoption of the ORLISTAT. The standard error of the log-normal distribution is about 4.6%.

3.2 Number of patients set by the purchaser

In this section we assume that the purchaser sets the number of treatments to provide, whereas the investment decision is left to the provider. Since *static efficiency* is ensured by definition of this case, we concentrate on the instruments available to the purchaser to ensure efficiency in the timing of investment.

Proposition 2 *When the provider is free to decide when to adopt the new technology, and the purchaser can set the number of treatments, the optimal timing of investment for the provider is characterized by the following threshold,*

$$\mu^*_{pr1} = +\sqrt{\left(\frac{2\beta}{\beta - 2}\right)(\rho I(1 - \gamma - \lambda))} \tag{12}$$

Proof:
The instantaneous payoff for the provider is obtained substituting the efficient number of patients ($x_t^s = \mu_t$) into eq. (7):

$$\Pi_t^{pr1} = \frac{\mu_t^2}{2} + \lambda\rho I \tag{13}$$

The corresponding *stopping value* is:

$$\Omega^{pr1}(\mu_t) = \frac{\mu_t^2}{2\rho} - I(1 - \gamma - \lambda)$$

The shape of the value function in the waiting region ($L\mu_t^\beta$) is the same as in the previous case (see Appendix), where $\beta > 1$ is the positive root of $\Psi(\beta) = 0$. Only the constant will be different in general, since the optimal threshold will be different[15]. In compact notation:

$$V^{pr1}(\mu_t) = \begin{cases} L\mu_t^\beta & \text{for } \underline{\mu} \leq \mu_t < \mu^*_{pr1} \\ \frac{\mu_t^2}{2\rho} - I(1 - \gamma - \lambda) & \text{for } \mu_t \geq \mu^*_{pr1} \end{cases} \tag{14}$$

The usual boundary conditions (*value matching* and *smooth pasting*) enable determination of the value of the constant L,

$$L = \frac{(\mu^*_{pr1})^{2-\beta}}{\rho\beta}$$

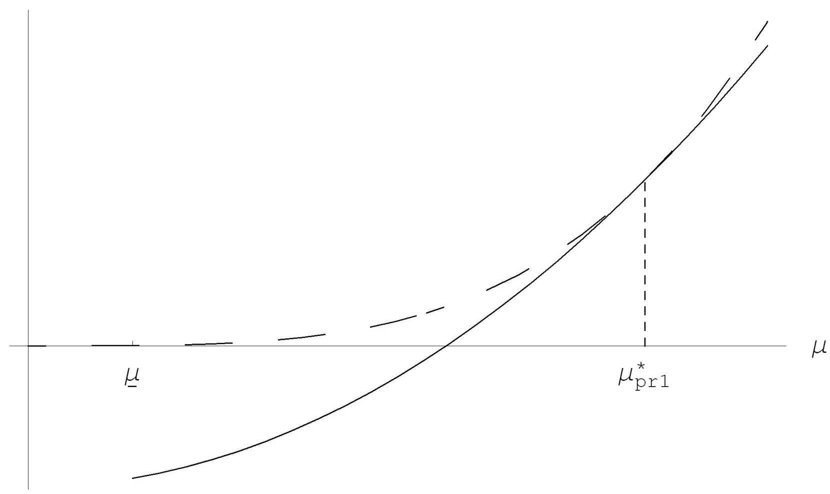
and hence the investment threshold in eq. (12) (Fig. 2). *Q.E.D.*

There is nothing to prevent the threshold as defined by eq. (12) from lying below $\underline{\mu}$. When this is the case the payment rule is sufficiently generous to induce the provider to invest at that level of μ, but the adoption is prevented[16]. When the

[15]The boundary conditions are employed to simultaneously determine the values of the threshold and this constant.

[16]In this case although the provider is still able to claim the right to invest at a later date, the stopping value equals zero over the whole range of values of μ. Therefore, provided that $\mu^*_{pr1} \geq \underline{\mu}$, we may drop the interval $0 \leq \mu \leq \underline{\mu}$ from the analysis.

Figure 2: Value Functions



number of patients treated can be controlled by the purchaser, the parameters γ and λ have identical effects (eq. (12)). In other words, the purchaser can make the investment by the provider more (less) likely by increasing (reducing) either the lump-sum payment γ or the difference between price and marginal cost through λ. The two instruments have perfectly symmetric effects.
The comparison between the threshold in eq. (12) and the one corresponding to the first best (eq. 8) shows that:

Corollary 1 *If the number of treatments is set by the purchaser, dynamic efficiency is attained by any payment scheme such that,*

$$\gamma + \lambda = \frac{a}{\rho I} \tag{15}$$

The above condition simply states that as long as $a > 0$[17] the lump-sum payment needed for a timely adoption of the new technology is increasing in the ratio between the benefit component of the adoption that the provider does not internalize and the investment cost. By Proposition 1 it is also worth noting that if $a = 0$ the purchaser can induce the optimal timing of investment by setting $\gamma = 0$ and $\lambda = 0$, i.e. when all patients receive the same benefit from the treatment, dynamic efficiency can be attained paying only the marginal cost.

[17]When $a < 0$, for example as a result of particularly strong competitive pressures towards adoption, the optimal policy would imply either a price below the marginal cost ($\lambda < 0$) or a sort of taxation of the adoption ($\gamma < 0$). However, the fact that these policies are far from real world payment rules may be taken as an indication that technologies with these characteristics are rare, to say the least. Therefore, in the rest of the paper we will focus on cases where $a \geq 0$.

This result depends on the specific form (linear) of the benefit function. As will be shown in Section 4, replacing this functional form with one with decreasing marginal benefits, $\gamma = 0$ and $\lambda = 0$ implies a higher threshold for the provider (i.e. a lower probability of investment) than for the purchaser, and subsequently the need for the purchaser to intervene either with lump-sum payment or by increasing the price above the marginal cost[18].

3.3 Number of patients set by the provider

Unlike in the previous section, here we assume that the provider can decide not only when to invest, but also the number of patients to treat. Technically speaking there is no particular difficulty in including the number of patients in a contract, nor, in most cases, in verifying it. However, the relevance of the international debate on *appropriateness* and *necessity* of treatments (Sistrom, 2009) suggests that the control of the number of treatments is difficult to implement, and divergences from levels deemed ideal are asymmetric, cases where patients in excess of the efficient level are treated being by far more frequent. Furthermore, thresholds on reimbursement are rarely treatment specific; they often include a wider range of activities of the hospital. Since in this case the provider can decide the mix of treatments, those with a comparatively large fixed cost component are likely to be the most convenient to expand. However, it can be shown that the quality of our results does not change, even when a threshold on the number of patients exists, as long as its level exceeds the efficient level.

Proposition 3 *When the provider can decide both the timing of adoption and the number of treatments, the timing of investment is characterized by the following optimal threshold,*

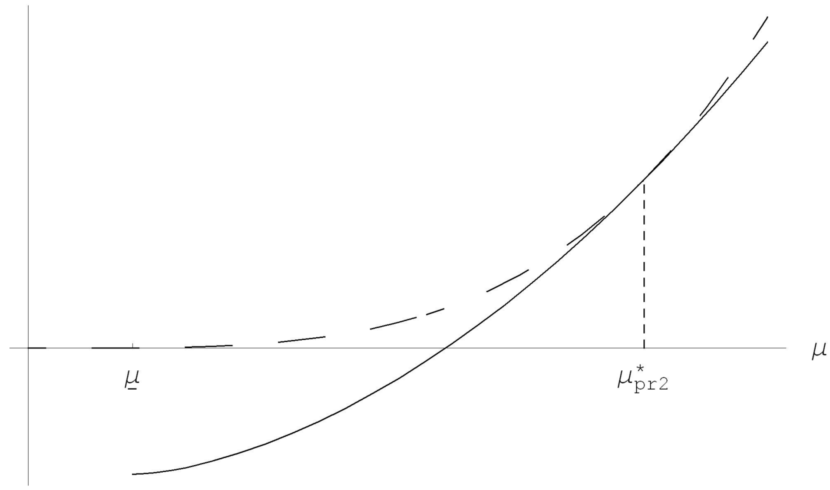
$$\mu^*_{pr2} = +\sqrt{\left(\frac{\rho\beta}{\beta-2}\right)\left[I(1-\lambda-\gamma)+\sqrt{I^2(1-\lambda-\gamma)^2-\left(1-\frac{4}{\beta^2}\right)\lambda^2 I^2}\right]} \tag{16}$$

Proof:
In each period, the provider decides the number of patients to treat in order to maximize its instantaneous profit (eq. (7)), which, in our simple setting, implies $x_t^p = p_t$ whilst, in setting the price, the purchaser still refers to the socially efficient number of patients $x_t^s = \mu_t$. Under these assumptions, the provider's instantaneous payoff function becomes:

$$\Pi_t^{pr2} = \frac{1}{2}\left[\mu_t + \frac{\lambda\rho I}{\mu_t}\right]^2 \tag{17}$$

[18] In this case, the benefit for each intramarginal patient exceeds the price so that in deciding when to adopt the new technology, the provider fails to internalize part of the patients' benefits. The result is a delay in the adoption. In other words, the decreasing marginal benefit plays a similar role to $a > 0$ in the base model.

Figure 3: Value Functions



The corresponding expected value of the investment (*stopping value*) is:

$$\Omega^{pr2}(\mu_t) = \frac{\mu_t^2}{2\rho} + \frac{\rho\lambda^2 I^2}{2\mu_t^2} - I(1-\lambda-\gamma)$$

which is always increasing in μ for $\mu \geq \underline{\mu}$.
We can write the provider's value function in compact form:

$$V^{pr2}(\mu_t) = \begin{cases} K\mu_t^\beta & \text{for } \underline{\mu} \leq \mu_t < \mu^*_{pr2} \\ \frac{\mu_t^2}{2\rho} + \frac{\rho\lambda^2 I^2}{2\mu_t^2} - I(1-\lambda-\gamma) & \text{for } \mu_t \geq \mu^*_{pr2} \end{cases}$$

By the standard boundary conditions at μ^*_{pr2} the following value for the constant K is obtained:

$$K = \frac{(\mu^*_{pr2})^{2-\beta}}{\rho\beta} - \frac{(\mu^*_{pr2})^{-2-\beta}}{\beta}(\rho\lambda^2 I^2)$$

Substituting this value into the *value matching* condition the threshold in eq. (16) is obtained. *Q.E.D.*.

Eq. (16) shows that in this case the effects of λ and γ on the optimal threshold are not symmetric. An increase in γ has the same effect as before. An increase in λ produces a further effect:

Corollary 2 *When the provider is free to set the number of treatments, any increase in λ anticipates the expected time of investment as a result of the provider anticipating the possibility of treating patients in excess of the efficient level.*

The last term on the right hand side of (16) captures the impact of an increase in λ on the adoption decision of the provider who anticipates the opportunity to repay investment costs exploiting the impossibility for the purchaser to enforce the efficient number of treatments[19]. This term implies a further decrease in the threshold, irrespective of the value of β[20]. This effect is added to that of the explicit reimbursement of capital costs embedded in the first two terms in brackets, which is equivalent to the one observed in the case where the number of patients is set by the purchaser (eq. (12)). Therefore, whenever $\lambda > 0$ the possibility for the provider to decide how many patients to treat implies a lower threshold and hence, *ceteris paribus*, an anticipation in the expected time of investment in comparison with the situation where only the marginal cost is paid for each patient.

4 The General Model

The specific functional forms of the benefit and cost functions adopted in the previous sections enable a closed form solution for the thresholds which implicitly define the timing of adoption of the new technology. In what follows, we show that all the key results discussed so far are valid even if the marginal benefit is decreasing in the number of patients treated and the marginal cost is increasing. In particular, we deem the extension to decreasing marginal benefits important, because most new health care technologies are shown to provide most benefits to patients with specific characteristics and the potential benefits decrease, or are at least more uncertain, as the treatment is provided to patients who are lacking in some of those characteristics. Appropriateness, i.e. ensuring that only patients who can really benefit from the treatment receive it, is a major issue in most health care systems. Therefore, this generalization may provide insights into the impact of alternative payment rules on adoption decisions and appropriateness in the provision of treatments.
The new benefit and cost functions are given respectively by,

$$b(x_t, \mu_t) = a + \mu_t x_t^{\theta} \tag{18}$$

and,

$$c(x_t) = x_t^{\delta} \tag{19}$$

with $0 < \theta \leq 1$ and $\delta > 1$.
The new number of patients that ensures static efficiency is,

$$x_t^s = \left(\frac{\theta \mu_t}{\delta}\right)^{\frac{1}{\delta - \theta}}$$

[19]This result would not hold if the purchaser was unable to commit to the rule. In that case, it would be *ex-post* efficient from his standpoint to set $\lambda = 0$ once the investment has been made. The provider would anticipate this and incorporate this parameter into the adoption decision.

[20]Note that the sign of this term is the same as that of the term multiplying the terms in brackets.

and consequently the price can be written as,

$$p_t = \delta \left(\frac{\theta \mu_t}{\delta} \right)^{\frac{\delta-1}{\delta-\theta}} + \lambda \rho I \left(\frac{\theta \mu_t}{\delta} \right)^{-\frac{1}{\delta-\theta}} \tag{20}$$

As in the base model, providers are free to decide when to invest in the new technology, but this decision is subject to the constraint set by the purchaser on the minimum value of effectiveness:

$$\mu \geq \left[\frac{\lambda \rho I}{\delta(\delta-1)} \left(\frac{\theta}{\delta} \right)^{-\frac{\delta}{\delta-\theta}} \right]^{\frac{\delta-\theta}{\delta}} \equiv \underline{\mu}_g$$

4.1 First Best

Using the same approach employed in the previous section, we can write the following value function for the first best:

$$V^{pug}(\mu_t) = \begin{cases} Z_g \mu_t^{\beta} & \text{for } \mu_t < \mu_{pug}^* \\ \frac{1}{\rho} \left[a + \mu^{\frac{\delta}{\delta-\theta}} \left(\frac{\theta}{\delta} \right)^{\frac{\theta}{\delta-\theta}} \left(\frac{\delta-\theta}{\delta} \right) \right] - I & \text{for } \mu_t \geq \mu_{pug}^* \end{cases} \tag{21}$$

By imposing the standard boundary conditions, the first best investment threshold for the generalized model is:

$$\mu_{pug}^* = \left[\frac{\rho I - a}{\left(1 - \frac{\delta}{\beta(\delta-\theta)} \right) \left(\frac{\theta}{\delta} \right)^{\frac{\theta}{\delta-\theta}} \left(\frac{\delta-\theta}{\delta} \right)} \right]^{\frac{\delta-\theta}{\delta}} \tag{22}$$

The impacts of the main parameters on the optimal investment threshold are consistent with those observed in the base model. Increases in the investment cost (I) and the parameter a have opposite effects on the timing of investment. The effect of the level of uncertainty is also the same: the threshold increases as β decreases, which means that, all else being equal, the investment occurs later in expected terms, the greater the value of σ.

4.2 Number of patients set by the purchaser

The instantaneous profit function for the purchaser is:

$$\Pi^{pr1} = (\delta - 1) \left(\frac{\mu \theta}{\delta} \right)^{\frac{\delta}{\delta-\theta}} + \lambda \rho I \tag{23}$$

This leads to the following value function:

$$V^{prg1}(\mu) = \begin{cases} L_g \mu^{\beta} & \text{for } \underline{\mu}_g \leq \mu < \mu_{prg1}^* \\ \frac{\delta-1}{\rho} \left(\frac{\mu \theta}{\delta} \right)^{\frac{\delta}{\delta-\theta}} - I(1-\lambda-\gamma) & \text{for } \mu \geq \mu_{prg1}^* \end{cases} \tag{24}$$

From these functions, the usual procedure can be used to obtain the optimal investment threshold for this case:

$$\mu^*_{prg1} = \frac{\delta}{\theta} \left[\frac{\rho I(1-\lambda-\gamma)}{(\delta-1)\left(1-\frac{\delta}{\beta(\delta-\theta)}\right)} \right]^{\frac{\delta-\theta}{\delta}} \tag{25}$$

As in the previous subsection, the consistency of the impact of changes in the main parameters with the case with linear benefits can be easily checked.

4.3 Number of patients set by the provider

As for the base model, we are mainly interested in the study of the case where the purchaser cannot enforce the socially optimal number of treatments. Given the price in eq. (20) the provider sets the number of treatments in order to maximize instantaneous profit, which becomes[21],

$$\Pi^{pr2} = (\delta-1)\left(\frac{p(\mu)}{\delta}\right)^{\frac{\delta}{\delta-1}} \tag{26}$$

The corresponding value function is:

$$V^{prg2}(\mu) = \begin{cases} K_g \mu^\beta & \text{for } \underline{\mu}_g \leq \mu < \mu^*_{prg2} \\ \left(\frac{\delta-1}{\rho}\right)\left(\frac{p(\mu)}{\delta}\right)^{\frac{\delta}{\delta-1}} - (1-\gamma)I & \text{for } \mu \geq \mu^*_{prg2} \end{cases} \tag{27}$$

where, μ^*_{prg2} is the optimal investment threshold for the provider with the generalized benefit and cost functions. It can be easily checked that the *stopping value* is always increasing in μ for $\mu \geq \underline{\mu}_g$.
Imposing the usual boundary conditions, the following equation implicitly defines the optimal investment threshold:

$$\frac{\mu^*_{prg2}}{\rho\beta}\left(\frac{p}{\delta}\right)^{\frac{1}{\delta-1}}\left(\frac{\partial p(\mu^*_{prg2})}{\partial \mu}\right) = \left(\frac{\delta-1}{\rho}\right)\left(\frac{p(\mu^*_{prg2})}{\delta}\right)^{\frac{\delta}{\delta-1}} - (1-\gamma)I \tag{28}$$

In order to help intuition the above equation can be rewritten in more compact notation:

$$\frac{\Pi^{pr2}}{\rho}\left[1 - \frac{\delta}{\delta-1}\frac{\epsilon_{p,\mu}}{\beta}\right] = (1-\gamma)I \tag{29}$$

where, $\epsilon_{p,\mu}$ denotes the elasticity of price with respect to the effectiveness parameter. Eq. (29) highlights the role on the elasticity in determining the existence and the level of the optimal threshold. A necessary condition for the existence of a threshold is that $\epsilon_{p,\mu} < \beta\frac{\delta-1}{\delta}$. If this does not hold, the value of investing (left hand side) is always less than its net cost. Alternatively, for very low values

[21] In order to keep the notation as simple as possible, the price is denoted as an implicit function of μ in the payoff and value functions.

of elasticity, there may also be no threshold because the value of investing is greater than its cost, independent of the level of effectiveness. In this case, the investment will always take place. Since the term in brackets is never greater than one for $\mu \geq \underline{\mu}_g$, and given that the first term on the left hand side is the Net Present Value of the investment, eq. (29) also shows a standard result in the real options literature, namely that the optimal threshold exceeds the NPV threshold. The difference between the two thresholds is greater, the smaller the value of β, i.e. the greater the uncertainty.

5 Policy

In this section, the policy implications of the results presented so far are discussed, also taking into account possible limitations on the set of instruments available to regulators.

5.1 Two instruments

The best possible scenario for the purchaser is one in which he can control the price level through λ and the lump-sum payment through γ. By setting λ to zero, static efficiency is ensured. By replacing this value into eq. (28), the problem of dynamic efficiency boils down to the one tackled in Section 4.2, because the provider treats the socially efficient number of patients when the price equals the marginal cost.

Proposition 4 *If the regulator can decide on both λ and γ, static and dynamic efficiency can be simultaneously ensured.*

Proof:
It is sufficient to prove that for $\lambda = 0$ a value of γ exists such that the provider's threshold equals the first best threshold. Setting the solution of eq. (28) for $\lambda = 0$ equal to the right hand side of eq. (22), the value of γ that ensures dynamic efficiency is obtained:

$$\gamma^* = 1 - \left(1 - \frac{a}{\rho I}\right)\left(\frac{\theta(\delta - 1)}{\delta - \theta}\right) \tag{30}$$

Eq. (15) is a special case of eq. (30) , for $\theta = 1$, $\delta = 2$ and $\lambda = 0$. *Q.E.D.*

Proposition 4 states that even when both the decision on the number of treatments and on the timing of investment are decentralized, static and dynamic efficiency can be simultaneously achieved if the regulator can use both parameters defining the payment rule. In order to ensure this result, a two-part tariff is necessary: a variable component should cover the marginal cost of provision; a lump sum paid upfront should instead be granted to cover a part of the capital cost. The optimal lump-sum payment depends on the characteristics of the technology, but not on the level of uncertainty. In particular, the portion of the investment cost to be immediately reimbursed is greater for targeted technologies (low θ) and for those whose marginal cost is comparatively flat (low δ).

Finally, large values of a obviously require a larger part of the investment cost to be immediately reimbursed.

5.2 Limitations on the instruments set

The above section suggests an easy solution to the problem of static and dynamic efficiency when both the instruments introduced in the model are available. The evidence on real reimbursement systems suggests that only some pricing schemes involve lump-sum payments. In actual health care systems there can be different reasons why the purchaser is unable or unwilling to pay at least part of the capital cost of the investment. It is not our objective here to explore the stimulating issue of why lump-sum contributions seem to be rather unpopular in the real world. Simply, having observed this, we try to investigate the policy implications when the price per patient (through λ) is the only instrument available to the regulator ($\gamma = 0$).

Corollary 3 *When the payment scheme involves no lump-sum component, a trade-off emerges between static and dynamic efficiency.*

Setting $\lambda = 0$ in eq. (28), the following threshold characterizes the provider's optimal timing of investment when he is free to set the number of treatments:

$$\widetilde{\mu}^* = \frac{\delta}{\theta}\left[\frac{\rho I(1-\gamma)}{(\delta-1)\left(1-\frac{\delta}{\beta(\delta-\theta)}\right)}\right]^{\frac{\delta-\theta}{\delta}} \tag{31}$$

which is greater than μ^*_{pug}[22]. This implies an inefficiently weak incentive for the provider to invest in the new technology. Since the derivative of μ^*_{prg2} with respect to λ is negative, at least locally (see the Appendix), starting from $\lambda = 0$ it is always possible to anticipate the expected time of investment by increasing the price above the marginal cost. Since μ^*_{prg2} is decreasing in λ, dynamic efficiency could be ensured by increasing the price above the marginal cost level. The price for inducing the provider to anticipate the investment in this way is the provision of the treatment to some patients for whom the marginal cost exceeds the marginal benefit.
The following corollary immediately follows from the application of the theory of the second-best to our problem:

Corollary 4 *When the regulator is constrained not to include any lump-sum component, it is second-best efficient to set λ at a level such that the provider's investment occurs later than in the first best.*

An obvious implication of the Corollary above is that if $\gamma = 0$ is seen as a constraint for the regulator, having technologies adopted later than would be

[22] It should be observed that, unlike in the base model, this is true also for $a = 0$ and for negative values of a, provided they are sufficiently close to zero.

socially efficient, which are used to treat patients in excess of the efficient level, may be second-best optimal. Besides the rare use of capital costs contributions, the relevance of the debate concerning appropriateness is another fact common to most health care systems. Underlying is the idea that too many patients receive some treatments once a technology is adopted, in particular even patients with characteristics such that the evidence on effectiveness or cost-effectiveness is lacking. The coexistence of these two phenomena (no capital cost contribution and the issue of appropriateness) perfectly fits into our model when the use of capital cost contribution is ruled out. Prices above marginal costs can be interpreted as a way to improve dynamic efficiency sacrificing some static efficiency. As seen above, when the number of patients treated cannot be controlled, the impact on the investment decision is twofold. The first effect is the pure contribution to capital costs embedded in the price (common to situations with and without control over patients), the second is related to the fact that the provider, at the time of deciding on the investment, anticipates the opportunity to exploit the difference between price and marginal cost to increase the number of patients and therefore revenues. In this context, the debate on appropriateness may be interpreted as an attempt to implement a control over the number of treatments, which would enable overcoming of the trade-off (Sections 3.2 and 4.2).

The policy question that naturally arises is what factors may contribute to mitigate the trade-off. From eqs. (8) and (16), the difference between the first-best and the decentralized threshold shrinks for comparatively low values of a. Therefore, competitive pressures towards technology adoption, or other factors reducing the value of the fixed effect, contribute to make the trade-off less binding when the possibility of making lump-sum payments by the purchaser is limited. However, the possibility for the regulator to influence the factors affecting the value of the fixed benefit of adoption a may be very limited.

The characteristics of our model lead to some further considerations. It has been assumed throughout the paper that provider and purchaser face symmetric uncertainty. The discussion above has concentrated on two standard instruments typically available for regulation: price and lump-sum contributions to capital costs. However, in our setting, the control of uncertainty by the regulator may be conceived as a further instrument when lump-sum payments are not available. It is assumed in the paper that provider and purchaser face symmetric uncertainty and variations in the stochastic variable μ are immediately and completely reflected by the purchaser in variations in the level of price paid (eq. (5)). However, the regulator could also decide to transfer variations in the stochastic variable only partially. As a standard result in the real options literature, the value of the option to postpone the investment is greater the greater the level of uncertainty. Hence, a reduction in the level of uncertainty leads to an anticipation of the expected time of adoption. Of course, in reality providers and purchasers face symmetric technological uncertainty. However, the regulator can reduce the level of uncertainty actually faced by the provider replacing the total and instantaneous adaptation of price that has been assumed so far, with a partial adaptation. Alternatively, lower and/or upper price boundaries

could be set.
Assuming that γ necessarily has to be set equal to zero, the extension of this concept to our framework suggests that a reduction in the level of uncertainty the provider faces could be used as an incentive to invest. This kind of incentive, unlike an increase in λ, has no negative implications for static efficiency. Of course, there is a price for the use of this instrument, which is related to the fact that some risk is transferred from the provider to the purchaser. However, this transfer could be efficient as long as the opportunities to diversify risk (across providers and technologies) are greater for the purchaser than for the provider.

6 The case of Positron Emission Tomography

In this section, we provide a numerical example by calibrating the model developed in Section 4 to fit the characteristics of Positron Emission Tomography (PET), one of the main innovations in diagnostic technologies in recent years. The decision that we study is the adoption of a PET scan, whose cost is about 3,800,000 euros[23]. In order to do this, we use the following cost function:

$$c(x_t) = 300x_t^{\delta}$$

We also assume that the net effect of the factors affecting a is such that $a = 10,000$ euros, and that the values of the technological parameters θ and δ are respectively 0.8 and 1.2.
To simplify the analysis, we keep working on an infinite time horizon, but we introduce a jump process describing the probability that in each period a new technology arrives, which makes PET obsolete. In other words, we assume that once PET has been adopted, it will be in use until a sufficiently ground-breaking innovation comes to replace it. In each period there is a given probability ϵ that PET becomes obsolete and therefore the number of examinations falls to zero. It can be shown that formally, these assumptions simply imply that the relevant discount rate becomes $\rho + \epsilon$ (Dixit and Pindyck, 1994, Ch. 4). We set $\rho = 5\%$ and $\epsilon = 5\%$, which implies that the expected length of the project is 20 years.
We study the static and dynamic efficiency properties of some regulatory settings by comparing respectively the actual with the efficient number of patients treated and the actual with the efficient investment threshold. Concerning the latter, it may be convenient to shift from a monetary measure of effectiveness like μ to a more readily interpretable measure like the QALY (*Quality adjusted life years*). This requires μ to be divided by the shadow value of a QALY gained[24]. We set this parameter equal to 30,000 euro, which is a value consistent with those usually employed in cost-utility analysis. Therefore, thresholds in terms of QALYs are simply obtained by dividing the monetary value of the threshold by 30,000.

[23]For a description of the main characteristics of the investment in PET, see Pertile et al. (2009)
[24]This parameter coincides with the threshold value for cost-utility analysis.

If the regulator can use both instruments, then static and dynamic efficiency can be simultaneously obtained by simply setting $\lambda = 0$ and γ according to the rule in eq. (30). In our case, a lump-sum payment covering 61% of the investment cost at the time of adoption (2,318,000 euros) would ensure the efficient timing of adoption. If lump-sum payments are not available, or there are constraints on the maximum amount that can be immediately reimbursed, both dimensions of efficiency cannot be simultaneously achieved. Let's first investigate how the optimal investment threshold varies for different levels of uncertainty assuming that the purchaser only pays the marginal cost for each patient ($\lambda = 0$, $\gamma = 0$).

Table 1: $\lambda = 0$;$\gamma = 0$

	σ	**0.01**	**0.08**	**0.15**
First-Best	Threshold	6,221	7,614	11,482
	Patients	711	1,178	3,289
	Price	1,339	1,480	1,818
Decentralized	Threshold	8,518	10,426	15,723
	Efficient no. patients	1,599	2,584	7,216
	Patients	1,599	2,584	7,216
	Price	1,566	1,732	2,128
Delta	Threshold (euro)	2,297	2,812	4,241
	Threshold (QALY)	0.077	0.094	0.141
	Patients	0	0	0

Table 1 shows the main results for this case for three different levels of uncertainty (1%, 8%, 15% standard deviation). For the first best, the table reports the optimal investment threshold (μ_{pug}^*), the efficient number of patients ($x^s(\mu_{pug}^*)$), and the corresponding price ($p(\mu_{pug}^*)$) calculated on the threshold. The corresponding information on "Threshold" (μ_{prg2}^*), "Patients" ($x^p(\mu_{prg2}^*)$) and "Price" ($p(\mu_{prg2}^*)$) is reported in the second part of the table for the decentralized solution (the provider decides how many patients to treat). This part of the table also reports the efficient number of patients given the provider's threshold ($x^s(\mu_{prg2}^*)$). This is different from the first best number of patients because decentralization implies that investment is undertaken for values of μ which are larger than the first best threshold ($\mu_{prg2}^{>}\mu_{pug}^*$). Since the threshold is higher, the efficient number of patients is larger. The lower part of the table shows the properties in terms of dynamic and static efficiency, through the differences in the thresholds (both in monetary terms and in terms of utility/effectiveness) and the number of patients treated. In particular, the comparison is between the first best and decentralization for the thresholds (rows 1 and 4), and between the actual and the efficient (given the decentralized threshold) number of patients (rows 5 and 6)[25].

For example, if the purchaser only pays the marginal cost for each patient, with $\sigma = 0.01$, the first-best investment should take place for values of μ at least as

[25]Since in our model static efficiency is only defined for a given level of effectiveness, the comparison between the first best number of patients and the decentralized number would be meaningless.

large as 6,221 euros, which is lower than the provider's threshold (8,518 euros). The difference (2,297 euros) corresponds to 0.077 QALYs. At the provider's threshold, the number of patients treated is efficient as a result of having set $\lambda = 0$, and therefore static efficiency is ensured. However, the delay in the expected time of adoption makes the situation dynamically inefficient. Table 1 also shows that uncertainty exacerbates the problem of dynamic inefficiency, reaching a difference of 0,141 QALYs with $\sigma = 0.15$[26].

Table 2: $\lambda = 0.35$;$\gamma = 0$

	σ	**0.01**	**0.08**	**0.15**
First-Best	Threshold	6,221	7,614	11,482
	Patients	711	1,178	3,289
	Price	1,339	1,480	1,818
Decentralized	Threshold	6,944	8,677	13,458
	Efficient no. Patients	935	1,632	4,891
	Patients	1,510	2,099	5,238
	Price	1,556	1,662	1,996
Delta	Threshold (euro)	723	1,063	1,976
	Threshold (QALY)	0.024	0.035	0.066
	Patients	575	467	347

Table 2 shows the role of uncertainty in determining the size of the trade-off when the lump-sum payment is not available ($\gamma = 0$). The parameter λ has been fixed at 0.35, so that the quality of this combination of parameters ($\gamma = 0$, $\lambda = 0.35$) is similar to that of a possible second-best from the purchaser's standpoint (Corollary 4)[27]. Since the change in λ is the only difference from Table 1, the first-best results are not affected. As a result of the increase in the price, the provider's threshold is reduced, and therefore the expected time of investment anticipated. The improvement in dynamic efficiency is shown by the smaller differences between the first-best and the provider's thresholds in Table 2, in comparison with Table 1. The drawback of raising the price above the marginal cost is a number of patients treated that exceeds the efficient level, as the last row in the table shows. It is interesting to see that the impact of uncertainty on static efficiency is different from that on dynamic efficiency. Whereas the first increases with uncertainty, moving from 0.024 QALYs to 0.066 QALYs, the second falls, moving from 575 patients more than the efficient level to 347.
The Table also provides some insights into point discussed at the end of the previous section, concerning the implications of purchaser and provider facing different levels of uncertainty. The purchaser's threshold with $\sigma = 0.08$ is 7,614 euros. For the provider, the thresholds are 6,944 and 8,677, respectively with

[26] In the discussion of the example we ignore the technical limits that imply a maximum number of treatments that can be provided in one period (around 2,500). In fact, this is the only case ($\lambda = 0$, $\gamma = 0$, $\sigma = 0.15$) among those considered, where the capacity limit is binding. Tables 2 and 3 show that when the payment parameters are efficiently set (first- or second-best) the number of treatments provided is within the capacity limit).

[27] See also Table 3.

$\sigma = 0.01$ and $\sigma = 0.08$. This suggests that there is a value of σ between these two values such that the decentralized threshold corresponds to the first-best, calculated for $\sigma = 0.08$. This means that if the uncertainty faced by the provider could be substantially reduced, the dynamic inefficiency of the situation described in Table 2 could be virtually eliminated.

Finally, we want to study the optimal policy by the regulator when lump-sum payments are not available ($\gamma = 0$) and therefore the trade-off between static and dynamic efficiency arises (Table 3). We do this by studying how the present value of the investment from the purchaser's standpoint changes as λ is increased, starting from $\lambda = 0$, assuming that the provider sets the number of patients (Table 3). Given the purchaser's objective function, the expected present value of the project is defined as:

$$\Psi = E_0 \left[e^{-(\rho+\epsilon)t_A} \right] \left[\frac{b(x^p) - c(x^p)}{\rho + \epsilon} - I \right] \tag{32}$$

It is shown in the Appendix that:

$$E_0 \left[e^{-(\rho+\epsilon)t_A} \right] = \left(\frac{\mu_0}{\mu^*_{prg2}} \right)^{\xi} \tag{33}$$

with $\xi > 1$.

Table 3: Second-best efficient pricing rule

	Dynamic eff.		Static eff.		Present Value
λ	**FB thresh.**	**Dec. Thresh.**	**Eff. patients**	**Dec. patients**	
0	0.275	0.377	3,160	3,160	1,829,170
0.1	0.275	0.363	2,886	2,995	1,923,420
0.2	0.275	0.348	2,585	2,812	2,030,650
0.3	0.275	0.328	2,240	2,599	2,148,090
0.38	0.275	0.307	1,899	2,385	2,226,890
0.39	0.275	0.304	1,848	2,353	2,231,310
0.4	**0.275**	**0.300**	**1,795**	**2,319**	**2,232,750**
0.41	0.275	0.297	1,739	2,283	2,220,680
0.42	0.275	0.292	1,677	2,243	2,220,680

The starting value of the stochastic parameter (μ_0) is set at 7,000 euros, with $\sigma = 0.1$. The other parameter values are as above. Table 3 shows the trade-off due to the increase in the price above the marginal cost. Increases in λ anticipate the investment thus reducing the gap from the first best threshold, but also increase the number of patients above the efficient level[28]. For the case under examination a value of $\lambda = 0.4$ yields the maximum present value for the investment, and hence the optimal trade-off. Consistently with the statement in Corollary 4 this second-best solution involves both static and dynamic efficiency.

[28]The number of patients in columns 4 and 5 are both calculated on the provider's threshold.

The former takes the form of a larger threshold and hence a delay in investment, with a difference of 0.025 QALYs. The latter leads to treat patients in excess of the efficient level (2,319 vs. 1,795). The comparison between the second best Present Value (2,232,750 euros) and the first best (2,437,640 euros), attainable with a lump-sum payment covering 61% of the investment cost and a fixed fee equal to the marginal cost, provides an estimate of the cost of the regulatory failure. In our case this is 204,890 euros.

7 Conclusion

The paper employs the typical instruments of the literature on irreversible investments under uncertainty to investigate the implications of alternative reimbursement rules. Although decisions with these characteristics are frequent in the health care sector (e.g. at the time of adopting innovative equipment) and often have substantial impacts on costs, specific regulation issues related to these have been rarely addressed in the literature so far. Moreover, there is a substantial variety among the solutions implemented in different health care systems.

A central issue investigated in the paper is the distinction and the interaction between static efficiency (providing the treatment to an efficient number of patients once the technology has been adopted) and dynamic efficiency (efficiency in the timing of adoption). If the purchaser is unable to set the level of patients at the efficient level, the choice of the payment scheme influences both the timing of adoption and the number of patients that receive the treatment. We have investigated the properties of a number of instruments available to the regulator to improve efficiency. If the purchaser can give the provider immediate reimbursement of a fraction of the capital cost (appropriately determined) when the provider decides to invest in the new technology, then both dynamic and static efficiency are obtained by simply paying the marginal cost for each patient treated. However, if for some reasons lump-sum payments cannot be used, a trade-off emerges between static and dynamic efficiency: the incentive to adopt the new technology when the price equals marginal cost, thus ensuring static efficiency, is too weak. In this case, the adoption of the technology occurs later than would be efficient.

The evidence from real world health care systems suggests that lump-sum reimbursements of capital costs are not frequently used. This may be due to either liability constraints for the purchaser or inability to differentiate the pricing rules for technologies with substantial capital costs (typically equipment). Although the investigation of exactly why this may be the case is beyond the scope of this work, our results provide a possible explanation of why appropriateness (provision of treatments only to those patients that really need it) is an issue in several health care systems. It is also interesting to note that the regulators in health care systems that are more sensitive to this issue are moving in the direction described in our model. In Switzerland the new DRG system that will come into force in 2012 foresees a model for capital reimbursement that is very

similar to the one we have presented in this paper[29]. The calibration of the model for the case of PET has provided a tentative estimate of the monetary cost of departing from the optimal payment rule, by relying only on the payment of a fixed price per patient.
For the health care systems that still use a pure DRG system , our model set-up enables the identification of instruments that could be used by the purchaser as a substitute for the immediate reimbursement of capital cost to foster dynamic efficiency. For example, setting boundaries to the variation of prices in response to changes of the stochastic variable, would reduce the variance actually faced by the provider and hence reduce the value of the option to postpone the investment.
Hopefully, these results will contribute to the development of the theoretical analysis of the incentives underlying specific purchasing rules when the provision of the service requires an irreversible commitment of resources. Our model could be developed in a number of directions. For instance, competition is only implicitly treated in our analysis through the impact on the fixed net benefit component. It would also be interesting to investigate the sensitivity of the results to changes in the objective functions of the purchaser and the provider. Finally, the interaction of the payment rule with other policy tools (e.g. a direct control by the purchaser on the timing of investment) could also provide useful insights. In particular, the reallocation of risk (uncertainty) between the purchaser and the provider as a policy tool could be a fruitful area for future research.

8 Appendix

Derivation of the value function in the waiting region:

The value of the project before the investment is made, $F(\mu)$, follows the following Bellman equation (Dixit and Pindyck, 1994):

$$\rho F(\mu) = lim_{dt\to 0}\frac{1}{dt}E[dF(\mu)] \tag{34}$$

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

$$E[dF(\mu)] = \alpha\mu\frac{\partial F(\mu)}{\partial \mu} + \frac{1}{2}\sigma^2\mu^2\frac{\partial^2 F(\mu)}{\partial^2 \mu} \tag{35}$$

The substitution of this into eq. (34) yields the following differential equation:

$$-(\rho+\delta)F(\mu) + \alpha\mu\frac{\partial F(\mu)}{\partial \mu} + \frac{1}{2}\sigma^2\mu^2\frac{\partial^2 F(\mu)}{\partial^2 \mu} = 0 \tag{36}$$

The general solution of this equation is,

$$Z_1\mu^{\beta_1} + Z_2\mu^{\beta_2}$$

[29]See http://www.swissdrg.org/fr/07_casemix_office/InformationenZuSwissDRG.asp?navid=11.

where, $\beta_1 > 1$ and $\beta_2 < 0$ are the solutions of eq. (9). The value of Z_1 and Z_2 is obtained imposing appropriate restrictions. First, for values of μ that tend to zero, the term $Z_2\mu^{\beta_2}$ would make the value jump to infinity. Of course, this is inconsistent with our problem, given that the provider is not allowed to invest for $\mu < \underline{\mu}$, and therefore the value of the corresponding opportunity to invest is zero. Therefore, Z_2 has to be set equal to zero. The value of Z_1 is determined simultaneously with the value of the optimal threshold, as explained in the text. Since Z_1 is the only relevant constant throughout, the subscript has been dropped in the text to simplify the notation.

The impact of increases in λ on μ^*_{prg2}:

$$\frac{d\mu^*_{prg2}}{d\lambda} = -\frac{\frac{d\Pi^{pr2}}{d\lambda}\frac{1}{\rho}\left[1-\frac{\delta}{\delta-1}\frac{1}{\beta}\varepsilon_{p,\mu^*_{prg2}}\right]-\frac{\Pi^{pr2}}{\rho}\frac{\delta}{\delta-1}\frac{1}{\beta}\frac{d\varepsilon}{d\lambda}}{\frac{d\Pi^{pr2}}{d\mu^*_{prg2}}\frac{1}{\rho}\left[1-\frac{\delta}{\delta-1}\frac{1}{\beta}\varepsilon_{p,\mu^*_{prg2}}\right]-\frac{\Pi^{pr2}}{\rho}\frac{\delta}{\delta-1}\frac{1}{\beta}\frac{d\varepsilon}{d\mu^*_{prg2}}}$$

The sign of this expression depends on that of the denominator. In order to simplify the notation, below we replace μ^*_{prg2} with μ^* in what follows.

$$\begin{aligned}
&= \frac{d\Pi^{pr2}}{d\mu^*}\frac{1}{\rho}\left[1-\frac{\delta}{\delta-1}\frac{1}{\beta}\varepsilon_{p,\mu}\right]-\frac{\Pi^{pr2}}{\rho}\frac{\delta}{\delta-1}\frac{1}{\beta}\frac{d\varepsilon}{d\mu^*}\\
&= \left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}-1}p'\frac{1}{\rho}\left[1-\frac{\delta}{\delta-\theta}\frac{1}{\beta}\right]-\frac{\delta}{\rho}\frac{1}{\beta}\left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}}\left(p''\frac{\mu^*}{p}+\frac{p'}{p}(1-\frac{\delta}{\delta-\theta}\frac{1}{\beta})\right)\\
&= \frac{1}{\rho}\left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}}\left\{p'\frac{\delta}{p}\left[1-\frac{\delta}{\delta-\theta}\frac{1}{\beta}\right]-\frac{\delta}{\beta}\left(p''\frac{\mu^*}{p}+\frac{p'}{p}(1-\frac{\delta}{\delta-\theta}\frac{1}{\beta})\right)\right\}\\
&= \frac{1}{\rho}\left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}}\left\{p'\frac{\delta}{p}\left[1-\frac{\delta}{\delta-\theta}\frac{1}{\beta}\right]-\frac{\delta}{\beta}p''\frac{\mu^*}{p}-\frac{\delta}{\beta}\frac{p'}{p}(1-\frac{\delta}{\delta-\theta}\frac{1}{\beta})\right\}\\
&= \frac{1}{\rho}\left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}}p'\frac{\delta}{p}\left[1-\frac{\delta}{\delta-\theta}\frac{1}{\beta}\right]\left\{1-\frac{\delta}{\beta}p''\frac{\mu^*}{p}-\frac{1}{\beta}\right\}\\
&= \frac{1}{\rho}\left(\frac{p}{\delta}\right)^{\frac{\delta}{\delta-1}}p'\frac{\delta}{p}\left[1-\frac{\delta}{\delta-\theta}\frac{1}{\beta}\right]\left\{\frac{\beta-1}{\beta}-\frac{\delta}{\beta}p''\frac{\mu^*}{p}\right\}
\end{aligned}$$

The sign of this expression is positive for $\lambda = 0$. Therefore, we can draw conclusions on a local result:

$$\frac{d\mu^*}{d\lambda}\mid_{\lambda=0}< 0$$

Proof of eq. (33)

The solution to $E_0[e^{-(\rho+\varepsilon)t_A}]$ can be obtained via the usual dynamic programming decomposition (Dixit et al., 1999 p.184).
Since the process μ_t is continuous, the expected discount factor is increasing in μ_0 and decreasing in μ^*_{prg2}; then it can be defined by a function $D(\mu_0;\mu^*_{prg2})$. Over the infinitesimal time interval dt, μ_t will change by the small value $d\mu_t$, hence we get the following Bellman equation:

$$(\rho+\varepsilon)D(\mu_0;\mu^*_{prg2})dt = E(dD(\mu_0;\mu^*_{prg2}))$$

By applying Itô's Lemma to dD we obtain the following differential equation:

$$\frac{1}{2}\sigma^2\mu^2 D'' + \alpha\mu D' - (r+\varepsilon)D = 0$$

We solve it subject to the two boundary conditions:

$$\lim_{\mu_0 \to 0} D(\mu_0; \mu^*_{prg2}) = 0$$

$$\lim_{\mu_0 \to \mu^*_{prg2}} D(\mu_0; \mu^*_{prg2}) = 1$$

and we get $D(\mu_0; \mu^*_{prg2}) = \left(\frac{\mu_0}{\mu^*_{prg2}}\right)^{\xi}$, where $\xi > 1$ is the positive root of the auxiliary quadratic equation $\Psi(\xi) = \frac{1}{2}\sigma^2\xi(\xi-1) + \alpha\xi - \rho = 0$.

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