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INVESTMENT DECISIONS IN HOSPITAL TECHNOLOGY WHEN PHYSICIAN ARE DEVOTED WORKERS

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Abstract

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1 Introduction

All advanced health care systems have to cope with the need to control expenditure growth without over-reducing investments in new technology, in order to guarantee patients adequate quality (Bokhari, 2001; Baker, 2001; Propper, 2004; HTC 2003). In this context, it is important to overcome the traditional (and somehow misleading) trade-off between cost and quality, where the latter is simply seen as a running cost[1]. In this paper, we argue that the quality of hospital care is determined by two main factors: the investment in medical technology, which is mostly irreversible[2], and the effort of the medical staff who have a more complex objective function than standard workers. The technological content of the treatment is the main determinant of clinical quality while the effort of the medical staff on behalf of the patients is the main input of relational quality[3]. Both clinical and relational quality contribute to determining the level of total quality of hospital services which is not however clearly related to the appropriateness of the treatment offered and to the actual health improvement of patients. Therefore, actual quality, although privately observable, cannot be verified before a court[4]. This is important for the purchaser of hospital care (e.g. an insurance plan, an HMO, or a public health authority) who pursues the objective of maximising total quality on behalf of its patients and needs to define a payment mechanism ("purchasing rule") that takes into account both the cost and the quality of health care knowing that the latter cannot be verified before a court. According to Arrow (1963) seminal paper and to more recent contributions on workers in non-profit organisations (Francois, 2000, 2003; Glazer, 2004), health care professionals could be considered

[1] See Harris (1979), Ellis and Mc Guire (1986), Newhouse (1996), Ma (1994), Rogerson (1994), Chalkley and Malcomson (1998, 2000 and 2002), Bigliaser and Ma (2003).

[2] More generally, irreversible investment by hospitals includes not only the adoption of new technologies (physical capital) but also investment in human capital. The irreversible part of the investment in human capital is represented by the investment in education and training of the staff for using specific technology, and the cost related to the recruitment of very specialised staff. Our analysis explicitly considers investment in physical capital but this is only a simplification, since the results we obtain hold also if the hospital's irreversible investment in human capital is considered.

[3] According to Campbell, Roland and Buetow (2000), there are two principal dimensions of quality of care for individual patients: access and effectiveness. We focus on effectiveness, considering its two key components: effectiveness of clinical care and effectiveness of inter-personal care.

[4] A variable can be verified before a court when it can be measured through an objective indicator. For the definition of observable but non-verifiable variables in contract theory, see e.g. Laffont and Martimort (2002).

"devoted workers" because they derive utility not only from the monetary rewards they receive but also from increasing their patients' health[5]. According to this approach, hospital physicians behave as devoted workers, since they are interested in the health outcome and the technology content of the productive process adopted, i.e. they are interested in promoting the total quality of hospital care. The features of the payment mechanism for hospital care set by the purchaser and the devoted characteristic of hospital physicians can strongly influence the investment decisions concerning new medical equipment taken by the hospitals. The empirical literature has shown that the decision to invest in new technology in health care is often postponed (Baker and Phibbs, 2002 a and b).We argue that this can happen for three main reasons. First, the costs of investment in health care technologies are highly sunk and there is uncertainty over future rewards as regards the price and the number of patients that will be treated. The real option literature shows that when an agent does not face a now-or-never investment decision, an option value of waiting emerges before undertaking a project involving sunk costs and uncertain payoffs (irreversibility effect). In other words, the agent may find it profitable to delay the investment, even when the project has a positive net present value. Second, the hospital may use the "devoted" characteristic of its physicians to substitute investment with effort in order to maximise its surplus, given a general payment rule for hospital care. Third, the purchaser may be unable to define an intertemporal purchasing rule that provides the right incentive for timely adoption of the new technology. In order to take account of these features, we develop a model which considers the behaviour of three main actors: an agency purchasing hospital care (the purchaser who pursues the objective of maximising total quality of hospital care on behalf of patients), a hospital (the provider) and a representative hospital physician. We consider the investment choices of the hospital and the effort decision of the hospital physicians in a two-period framework where investment is irreversible and doctors are "devoted workers". In particular, our model assumes that hospital physicians are intertemporally devoted, i.e. they determine their effort at the beginning of the period considered and commit themselves to the same level throughout. Since investment costs in health care technologies are highly sunk and there is uncertainty over future rewards, we use a real option approach[6] to determine the level of capital invested and its timing. To

[5] Arrow (1963) points out that health care professionals are strongly influenced by ethical norms, standards of care and service motives. Other interesting examples of devoted workers are firemen and university professors.

[6] See Dixit and Pindyck (1994) and Abel et al. (1996).

date there have been few attempts to model health care from a real option perspective. Exceptions are given by Palmer and Smith (2000), Driffield and Smith (2007), and Levaggi and Moretto (2004). Palmer and Smith (2000) seek to model the adoption of a new technology as an options problem while Driffield and Smith (2007) aim at assessing the methodological and practical implications of applying real options analysis to a clinical decision-making problem in which deferral is considered a relevant alternative[7]. Our model represents an extension and a generalisation of the analysis of Levaggi and Moretto (2004) who consider the case where the hospital's medical staff is not devoted and the investment decision is the result of a non-cooperative game between the physician and the hospital in a setting where the quality of hospital care can be observed (even by both actors) but not verified (i.e. it cannot be enforced before a court)[8]. In the more comprehensive two-period model presented here, hospitals can use the devoted characteristic of the physician to substitute investment with doctor's effort in order to maximise its intertemporal surplus. The model analyses how the purchaser may influence the timing of the hospital's investment decisions through the strategic setting of the parameters of a very general long-term contract ("purchasing rule") aimed at promoting total hospital care quality. According to this rule, the purchaser sets a quality-contingent long-term contract with the hospital according to a particular prospective payment scheme. This scheme provides for a cap on the volume of admissions paid by the purchaser, which can be raised only if the hospital increases the quality of provided care. In particular, we show that if physicians are devoted workers and the purchaser aims at accelerating the adoption of new technology, it is not optimal to set a purchasing rule that cancels out the option to defer the hospital's investment.[9]. The paper is organized as follows. Section 2 presents the basic

[7] In particular, Driffield and Smith (2006) demonstrate how the methods used to price financial options can be used to decide when to pursue a watchful waiting strategy for a particular patient. Watchful waiting is a form of clinical management under which immediate curative treatment is not given. Instead the patient undergoes a period of observation during which periodic tests monitor the progression of the illness.

[8] Also Bös and Fraja (2002) study a game between a health care authority and a hospital over the investment in quality. However, they do not consider the intertemporal aspect of the investment in health care and the specific effort of the medical staff in determining the level of quality. Furthermore, they allow the purchaser to rely on outside providers to induce the hospital to increase its investment.

[9] This contrasts with the result obtained by Levaggi and Moretto (2004) who showed that the problem of non-verifiability of quality could usually be avoided by a purchasing rule linking the volume of current care to be reimbursed to the investment made in the past periods, which induces the hospital to anticipate the investment.

model and the purchasing rule. Section 3 describes the Nash equilibrium of the game between the hospital and a representative physician for a general specification of the purchasing rule. In section 4, the Nash equilibria for different specifications of the purchasing rule are compared and the related policy implications are analysed. Section 5 shows how the purchaser could set the parameters of the purchasing rule in order to maximise total quality of hospital care. Lastly, section 6 concludes.

2 The model

To simplify the analysis, we assume that patients admitted to the hospital can be affected by one disease that requires a standard treatment; moreover, we assume that all the care delivered is appropriate. We consider a two-period model. Total quality q_t, $t = 1, 2$ is determined by both clinical and relational quality, as explained in the next section. Both capital and doctors' efforts contribute to its level. A new technology for producing hospital care is available at time 1 and the hospital may decide the level of investment (i.e. the number of technology units) in each period.We also assume that, once the investment in the new technology is undertaken, it cannot be diverted and depreciation is absent[10].

2.1 Quality and its aspects

In health care, quality is quite a controversial matter because its most natural definition - the outcome in terms of health gain of each patient - cannot be objectively measured since it depends on specific characteristics of the patient. For this reason, quality can be proxied by input or process variables and this means that while quality can be subjectively observed (at least on average terms), it cannot be verified before a court[11]. Chalkley and Malcomson (2000) define quality as a multivariable vector that includes all the aspects of hospital care such as the appropriateness of the treatment, the investment in technology that benefits the recipients and other aspects that are not strictly medical but that can improve hospital output, such as patient accessibility and hotel quality. Campbell, Roland and Buetow

[10] Together with irreversibility of investment, this assumption avoids the need to consider operating options for the hospital such as reducing output or even shutting down, and thereby considering reducing variable costs. For further details on this issue see e.g. Dixit and Pindyck (1994).

[11] Even when quality is observable, it would anyway be non-contractable because the clause would not be enforceable. On this point see Laffont and Martimort (2002).

(2000) consider two principal dimensions of health care quality: access and effectiveness. We partly follow the Campbell, Roland and Buetow approach, focusing on the effectiveness and considering its two key components: clinical and inter-personal care[12] denoted as q^c and q^r respectively. Clinical quality can be written as:

$$q^c = q^c(k) \tag{1}$$

where k represents the level of capital invested in medical technology. The underlying assumption is that the latter is important to improve hospital care and it is the key indicator used by the patient and the purchaser to evaluate the degree of innovation of the treatment offered. The relational quality is assumed to be a function of the effort of the hospital's staff devoted to patient-centered care (Stewart, 1995, 2000), that is:

$$q^r = q^r(e) \tag{2}$$

The term q^r captures important aspects relating to the quality of the relationship between the patient and the hospital staff: appropriate information on the therapy and its likely effectiveness, shared motivation with doctors and other personnel as regards the therapy, establishing a satisfactory human relationship with staff, etc. In our model we focus on the relational quality determined by the effort of hospital physicians devoted to the relationship with patients. Relational and clinical quality can be interpreted as two intermediate outcomes in the process leading to total quality. Therefore, total quality of hospital care is defined as:

$$q = F(q^c(k), q^r(e); \beta) = g(k, e; \beta) \tag{3}$$

where β is a random parameter that captures the unknown characteristics of patients that can influence the health outcome, as well as all the other uncertain determinants influencing input productivity. For the relational and clinical quality, the usual marginal properties hold: $F(0, q^c) \geq 0$, $F(q^r, 0) \geq 0$, $g_e > 0, g_k > 0$, $g_{ee} < 0, g_{kk} < 0$. In addition, we assume that $g_{ke} < 0$. The latter assumption states that the two qualities are substitutes. For example, having a better diagnostic technology could allow doctors to devote more time to communication with patients since it reduces the effort required to produce the diagnosis of patients' illnesses. We complete these

[12] By doing so, we implicitly assume that access to hospital services and hotel-related quality (e.g. measured by number of beds per room, private telephones, nurses per ward, availability of particular ancillary services, etc.) are set at a standard level. In any case, this assumption is made for the sake of simplicity, since our main results hold even when accessibility is considered as another dimension of hospital quality.

properties by assuming that $g_{k\beta} > 0$, $g_{e\beta} = 0$. That is, the shock β influences clinical quality but not the relational quality. The different impact of patient heterogeneity β needs to be discussed. For clinical quality the ability of the patient to recover is clearly a crucial element in determining the outcome and the productivity of health care. For relational quality, the productivity of an extra unit of the physician's effort is not influenced by health characteristics (i.e. the severity of illness) of patients even though it could be influenced by patients' behaviour.

2.2 The actors

In this paper we model the behaviour of three main actors: an agency purchasing hospital care (the purchaser), a hospital (the provider) and a representative physician.

2.2.1 The purchaser

The purchaser pursues the objective of maximising total quality on behalf of the patients.[13] It rewards the hospital a fixed price p for each treatment[14] and sets a quality-contingent long-term contract with the hospital according to a particular prospective payment scheme. This scheme provides for a cap x (≥ 0) on the volume of admissions which can be initially paid by the purchaser[15]. It can be raised only if the hospital increases the quality of provided care. In particular, in the second period the number of patients increases according to the following linear purchasing rule:

$$x_2(q_1, q_2) \equiv x + \gamma q_1 + \alpha(q_2 - q_1) \tag{4}$$

where q_1 is the level of total quality in the first period, $q_2 - q_1$ is the increase of quality from period 1 to period 2, and γ and α represent the relative weights. The rule (4) is quite general and responds to the need often advocated (National Audit Office, 1995) to use more sophisticated payment rules to increase the performances of the health care system. It can be interpreted in this way: each hospital, by increasing total quality (in both periods) can increase the number of admitted (and rewarded) patients. Therefore, rule (4) could represent either a situation in which the purchaser

[13] In this respect, it can be considered a perfect agent of the patients.

[14] Price p can be either a DRG tariff or any other form of prospective price for a specific treatment based on marginal cost of production.

[15] In this way the purchaser implicitly sets an expenditure cap px, e.g. in order to control moral hazard by the hospital.

buys more treatments from higher quality hospitals on behalf of the patients it represents or a situation in which higher quality hospitals attract more patients who are free to choose their preferred provider (and the purchaser pays for the increased admissions to higher quality hospitals). For example, in the US an HMO could set the number of patients to be treated in each hospital according to some quality indices (e.g. consumer health ratings); a similar situation could be depicted considering the purchasing role of Health Authorities within the British NHS and the star ratings recently proposed in order to ascertain the performance of hospital trusts (Jacobs, Goddard and Smith, 2006). In the somewhat different environment of the Italian NHS, where patients are free to choose the preferred hospital, a Local Health Authority (the purchaser) could remove (reduce) part of the yearly ceiling set on the number of treatments when the hospital increases the quality of treatments. In all these examples, quality can be indirectly promoted by a very general purchasing rule such as (4) built on a basic prospective payment scheme, by raising the cap x on the number of admissions which can be reimbursed by the purchaser after ascertaining (in the second period) that the hospitals have increased the total quality of the provided care.[16] In our paper we focus on four possible combinations of the purchasing rule (4) which represent alternative strategies the purchaser can follow to incentivate total hospital quality. They are:

- $\gamma - \alpha > 0$ and $\alpha > 0$: the number of patients reimbursed at $t = 2$ depends on the level of quality in both periods (we call this the general case)
- $\gamma > 0$ and $\alpha = 0$: the number of patients reimbursed at $t = 2$ depends only on the quality level reached at time $t = 1$
- $\gamma = \alpha$: the number of patients reimbursed at $t = 2$ depends on the quality level at time $t = 2$
- $\gamma = 0$ and $\alpha > 0$: the number of patients reimbursed at $t = 2$ increases only if the level of total quality in the second period is higher than the level reached at $t = 1$.[17]

[16] It must be pointed out that, following rule (4), higher quality hospitals are rewarded with more admissions bought at a given price p; however, the results hold even if the number of admissions were set constant, while the price varies according to quality levels.

[17] We do not consider a fifth possible case: $\alpha > 0$, $\gamma > 0$ and $\gamma - \alpha < 0$. In fact, in this case, the purchaser would provide a negative incentive for hospital care quality at time $t = 1$.

2.2.2 The physician

Hospital physicians cannot be adequately represented by the paradigm of the "selfish economic agent". As Arrows pointed out in his seminal analysis of the medical market, physicians' behaviour "is supposed to be governed by a concern for the customer's welfare which would not be expected of a salesman" and "there is a 'collectivity-orientation', which distinguishes medicine and other professions from business, where self-interest on the part of participants is the accepted norm" (Arrows, 1963, p. 949). In other words, physicians derive utility not only from the monetary rewards they receive but also from increasing their patients' health. Similarly to Arrows' analysis, a new strand of the literature on labour supply considers the existence of "devoted workers" that derive utility from the salary they receive and from the output they produce (Francois, 2000, 2003; Glazer 2004). According to this strand of literature, doctors could be considered devoted workers because they receive utility from increasing their patients' health. In our model this assumption is represented in the utility function of physicians which is made dependent on the health outcome and the technology content of the productive process adopted by the hospital, i.e. they are interested in promoting the total quality of hospital care. This assumption can be justified on several grounds: the doctor could be considered a benevolent agent that truly believes that better health outcomes for patients can be achieved through progress in medical technology; he might think that technology, by enabling more effective care, allows a satisfactory relationship to be established with the patients. Further, we assume that $e_t = \sup_{s \in (0,t)} e_s$: the effort at t cannot be lower than the maximum level of effort chosen up to time t. This assumption reflects the fact that most devoted physicians behave as if their effort were irreversible. For example, after setting her/his effort level at t=1 when the hospital buys a CAT scan, it is reasonable for the physician not to decrease his effort in relational quality if the hospital buys a second scan at $t = 2$. This implies that although investment in new technology and the physician's effort are substitutes in determining current total quality (since $g_{ke} < 0$), they are complements over time. Finally, we assume that the doctor's effort consists of two components. The first is a minimum level of effort e_l, which can be defined as "the monitored effort of the doctor", and is delivered independently of the adoption of the new technology by the hospital (we assume without losing in generality that $e_l = 0$). The second component is a level of effort delivered at each time which cannot be observed or verified by the other actors.[18] The hospital hires doctors at the constant exogenous wage w; the private cost for the unverifiable effort e is defined by $m(e)$, with $m' > 0$ and $m'' > 0$. By the above assumption, the physician's utility function in the first and second periods is:

$$B^1(k_1, e_1; \beta_1) \equiv w + vq_1(k_1, e_1; \beta_1) - m(e_1) \tag{5}$$

and:

$$B^2(k_2, e_2; \beta_2) \equiv w + vq_2(k_2, e_2; \beta_2) - m(e_2) \tag{6}$$

where v is the doctor's evaluation of each unit of quality.

2.2.3 The hospital

The hospital, being a surplus maximisers want to minimise costs. In our model the hospital cares about quality only through the purchasing rule (4). It stipulates a contract with the purchaser that foresees the payment of a prospective price p, net of operating costs, for each treatment.[19] In each period, the hospital can invest in a new technology at unit cost r[20]. Then capital accumulation is given by $k_2 = k_1 + i_2$, where i_2 denotes investment in period 2. Both the investment and the effort made by the physician determine the level of total quality according to (3). By the above arguments, the hospital net surplus in the first period is:

$$R^1(k_1, e_1) \equiv px \tag{7}$$

and in the second period is:

$$\begin{aligned} R^2(k_1, k_2, e_1, e_2; \beta_1, \beta_2) &\equiv px_2(q_1, q_2) \\ &\equiv p[x + \gamma q_1(k_1, e_1; \beta_1) + \alpha(q_2(k_2, e_2; \beta_2) - q_1(k_1, e_1; \beta_1))] \end{aligned} \tag{8}$$

[18] Following the literature on the devoted worker (Francois, 2000, 2003; Glazer, 2004), we assume that the doctor is not paid for the unverifiable effort, though this assumption can be relaxed without substantially changing the results.

[19] This is a simplifying assumption that does not alter the results. In general, the hospital faces some operating costs in running the new technology and these operating costs may differ from period to period due to the nature of the investment decision. In general, these costs are higher in the first period due to set-up costs, such as learning cost and human capital formation, and lower in the subsequent periods (Levaggi and Moretto, 2004).

[20] In this article, we assume that the investment cost does not change over time. However, the results do not change if we assume that the investment cost at time 2 is lower than at time 1, i.e. $r_2 < r_1$ (Levaggi and Moretto, 2004) or decreases with the dimension of the project, i.e. $r(k)$ with $r'(k) < 0$ (Dixit, 1993).

2.2.4 Information structure and timing

The purchasing rule (4) defines a long-term contract between the purchaser and the hospital. However, since quality and physicians' efforts are non-contractable, our model may present several forms of asymmetry of information among the three actors considered here. In particular, we assume that in each period:

- No one of the three actors is able to verify the current level of total quality q_t, $t = 1, 2$;
- The purchaser and the hospital cannot directly verify the physician's effort e_t, $t = 1, 2$.

Yet, since quality is a function of both the investment by the hospital and the physician's effort, we also get:

- The contribution of the capital to the current quality level is not fully verifiable by both the purchaser and the physician[21].

However, since in our two-period model the purchaser may observe ex-post the hospital capital k_1 and the doctor's efforts e_1:

- The purchaser may always verify ex post q_1 before a court (or a health care authority).

By the above assumptions, the timing of the model can be summarised as follows. At the beginning of period 1, the purchaser announces the purchasing rule (4) and the price p. The hospital and the physician, knowing β_1 and the purchasing rule, decide non-cooperatively k_1 and e_1 respectively. At the beginning of period 2, q_1 becomes verifiable, nature reveals β_2 and, conditional on k_1 and e_1, the hospital chooses k_2 and the doctor e_2.

3 Effort and investment decision

In this section we derive the Nash equilibrium of the game between the hospital and the physician corresponding to the general specification of the

[21] Intuitively, given that quality is not verifiable, even if the physicians can observe the level of investment in new technology, they cannot claim a high result in quality by the provision of their effort. For a general definition of observable but non-verifiable variables in contract theory, see e.g. Laffont and Martimort (2002).

purchasing rule (4) (i.e. $\gamma - \alpha > 0$ and $\alpha > 0$). Given the purchasing rule (4) and the information set, the hospital and the doctor choose simultaneously at each time t their state variables ($k_1, k_2, e_1, \hat{e}_2$) non-cooperatively. As for β, we assume that in the first period, β_1 is known and normalised to 1 while, in the second period, $\beta_2 \equiv \beta$ is stochastic and its realisation is characterised by the cumulative distribution $\Phi(\beta)$ with density $\Phi'(\beta) > 0$ on $\beta \in [0, \infty)$, which is known by all the actors[22]. Before defining the physician's and the hospital's choices, we need to consider the ex-ante objective function of both the actors. For simplicity, hereafter, we will omit $\beta_1 \equiv 1$ in the formulae.

3.1 The physician's ex-ante objective function

Let's start by analyzing the physician's decision in the first period.

- **First period**

As the physician is free to change her/his effort in the second period, by (5), the optimal effort at time $t = 1$ is simply given by the first order condition:

$$B_e^1(k_1, e_1) \equiv vg_e(k_1, e_1) - m'(e_1) = 0 \tag{9}$$

which implies: $e_1 = e_1(k_1)$.

- **Second period**

In the second period, conditional on k_2, the effort is given by:

$$B_e^2(k_2, e_2) \equiv vg_e(k_2, e_2; \beta)] - m'(e_2) = 0 \tag{10}$$

from which we get $\hat{e}_2 = \hat{e}_2(k_2)$. However, as $g_{ek} < 0$ and $k_2 \geq k_1$, the doctor will set $e_2 = \sup(e_1(k_1), \hat{e}_2(k_2) \equiv e_1(k_1)$. Therefore, omitting the time variable for the effort, we can conclude that the doctor's ex-ante objective function is:

$$B(k_1, k_2, e) = B^1(k_1, e) + \delta \int_0^{\infty} B^2(k_2(\beta), e; \beta) d\Phi(\beta) \tag{11}$$

where the second term on the r.h.s does not depend on k_1.

[22] As in Bös and De Fraja (2002), we assume that there is symmetry of information about the technology.

3.2 The hospital's ex-ante objective function

The hospital chooses the level and timing of its investment knowing that the latter is irreversible. In particular, if in period 1 the hospital makes an investment that it cannot resell in period 2 and future capital returns are uncertain, this investment decision involves the exercise of an option. Because of this uncertainty, the opportunity of waiting to learn more about the future productivity level has a timing premium (i.e. a holding value). We start by describing the hospital action in the second period, given the stock of investment k_1 inherited from period 1 and the physician's effort e. We then step back and show how the marginal profit in the first period depends on the hospital's expected action in the second period.

Second period

By (8), (4) and (3), the hospital's surplus at time 2 can be written as:

$$\begin{aligned} R^2(k_1, k_2, e; \beta) &\equiv p[x + \gamma q_1(k_1, e) + \alpha(q_2(k_2, e; \beta) - q_1(k_1, e))] \\ &\equiv p[x + (\gamma - \alpha)g(k_1, e) + \alpha g(k_2, e; \beta)] \end{aligned} \tag{12}$$

The assumptions on q guarantee that $R^2_{k_2}(k_1, k_2, e; \beta)) \geq 0$ is continuous and strictly decreasing in k_2 and continuous and strictly increasing in β (see Appendix A). Then, for a given stock of k_1 inherited from period 1 and physician's effort e, we can define a critical value of β (i.e. $\tilde{\beta}$) such that:[23]

$$R^2_{k_2}(k_1, e; \tilde{\beta}) \equiv p\alpha g_{k_2}(k_1, e; \tilde{\beta}) = r \tag{13}$$

At the beginning of period 2, nature reveals β and the hospital adjusts its stock of capital to the new optimal level that we identify as $k_2(\beta)$. The stock of capital must satisfy the constraint:

$$k_2(\beta) \geq k_1 \tag{14}$$

Thus, depending on the inherited stock k_1 and e, from (13) it emerges that when $\beta > \tilde{\beta}(k_1, e)$, it is optimal for the hospital to invest in extra units of

[23] By assumptions on (3) we get:

$$\frac{\partial \tilde{\beta}}{\partial r} = \frac{1}{p\alpha g_{k\beta}} > 0 \qquad \frac{\partial \tilde{\beta}}{\partial k} = -\frac{g_{kk}}{g_{k\beta}} > 0$$

and

$$\frac{\partial \tilde{\beta}}{\partial e} = -\frac{g_{ke}}{g_{k\beta}} > 0$$

technology up to the point where the marginal return equals the marginal investment cost r. On the other hand, when $\beta < \tilde{\beta}(k_1, e)$ the profit is so low that the hospital finds it convenient not to invest, so $k_2(\beta) = k_1$.

First period

By using the option decomposition proposed by Abel et al. (1996), we can show that:

Lemma 1 *The value of the hospital's investment can be written as:*

$$V(k_1, e) \equiv G(k_1, e) - \delta O(k_1, e) \tag{15}$$

where:

$$G(k_1, e) \equiv px + \delta p[x + (\gamma - \alpha)g(k_1, e) + \int_0^{\infty} \alpha g(k_1, e; \beta) d\Phi(\beta)]$$

$$O(k_1, e) \equiv \int_{\tilde{\beta}}^{+\infty} \{-[p\alpha g(k_2(\beta), e; \beta) - rk_2(\beta)] + [p\alpha g(k_1, e; \beta) - rk_1]\} \, d\Phi(\beta)$$

and δ is the discount factor.

Proof. See Appendix A ■

The term $G(k_1, e)$ is the hospital's expected present value of returns, keeping the stock of capital fixed at k_1. This can be interpreted as the hospital's value when it does not expand its investment in the second period. The term $O(k_1, e)$ indicates the value of the (*Call*) option to expand the capital in the second period if β rises above $\tilde{\beta}$. Equation (15) has an interesting and immediate interpretation: when the hospital invests in period 1 it gets the value $G(k_1, e)$ but it gives up the opportunity or option to invest in the future, valued at $O(k_1, e)$. The non-contractability of k_1 and e in the first period implies that the investment decisions by both actors are taken non-cooperatively. In this respect, equations (11) and (15) constitute a two-person normal form game. Therefore, we need to derive the best reply functions of the two actors.

3.3 The physician's best reply function

Since the second term on the r.h.s. of (11) does not depend on k_1 and the level of effort is constant over time, the physician's reaction curve is derived from his first order condition (9). Moreover, since:

$$B^1_{ee}(k_1, e) \equiv vg_{ee}(k_1, e) - m''(e) < 0$$

for any given value of k_1 a unique value e^* exists satisfying equation (9). The total differential of (9) yields:

$$\begin{aligned} \frac{de}{dk_1}_{|e=e^*} &= -\frac{B^1_{ek_1}(k_1, e)}{B^1_{ee}(k_1, e)} \\ &\equiv -\frac{vg_{ek}(k_1, e)}{vg_{ee}(k_1, e) - m''(e)} \end{aligned} \tag{16}$$

Since the two inputs are substitutes in determining current quality of hospital care, i.e. $g_{ek}(k_1, e) < 0$, the physician's reaction curve slopes downwards. This assumption appears plausible: an increase in the doctor's effort somehow reduces hospital investment in capital, and vice versa. This is represented by the curve DD in Figure 1.

Figure 1 about here

3.4 The hospital's best reply function

Similarly, the hospital's reaction function is obtained by the first-order condition on (15). The optimal amount of capital in period 1 depends on the marginal benefits and the marginal costs:

$$V_{k_1}(k_1, e) \equiv G_{k_1}(k_1, e) - \delta O_{k_1}(k_1, e) = r \tag{17}$$

where:

$$\begin{aligned} G_{k_1}(k_1, e) &\equiv \delta p[(\gamma - \alpha)g_{k_1}(k_1, e) + \int_0^{+\infty} \alpha g_{k_1}(k_1, e; \beta)]d\Phi(\beta)] \\ &= \delta p\gamma g_{k_1}(k_1, e) + \int_0^{+\infty} \delta p\alpha[g_{k_1}(k_1, e; \beta) - g_{k_1}(k_1, e)]d\Phi(\beta)] \end{aligned}$$

$$O_{k_1}(k_1, e) \equiv \int_{\tilde{\beta}}^{+\infty} [p\alpha g_{k_1}(k_1, e; \beta) - r]d\Phi(\beta) \geq 0$$

Equation (17) emphasises the role played by the option pricing approach in determining the stock of capital in period 1. The hospital optimal behaviour does not simply require the equalisation of the expected present value of marginal returns in the first period $G_{k_1}(k_1, e)$ and the marginal cost of the investment r. In fact, costs are represented by the price of the investment, r, plus the value of the marginal call option, $O_{k_1}(k_1, e)$, as investing in period 1 means giving up the opportunity of deferring the investment. Moreover, since:

$$\begin{aligned} V_{k_1k_1}(k_1, e) &\equiv G_{k_1k_1}(k_1, e) - \delta O_{k_1k_1}(k_1, e) \\ &\equiv \delta p(\gamma - \alpha) g_{k_1k_1}(k_1, e) + \delta \int_0^{+\infty} p\alpha g_{k_1k_1}(k_1, e; \beta)) d\Phi(\beta) \\ &\quad -\delta \int_{\tilde{\beta}}^{+\infty} p\alpha g_{k_1k_1}(k_1, e; \beta) d\Phi(\beta) \\ &\equiv \delta p(\gamma - \alpha) g_{k_1k_1}(k_1, e) + \delta \int_0^{\tilde{\beta}} p\alpha g_{k_1k_1}(k_1, e; \beta)) d\Phi(\beta) < 0 \end{aligned}$$

for any given value of r and e, a unique value of k_1^* exists satisfying equation (17). The total differential of (17) can be written as:

$$\frac{dk_1}{de}_{|k_1 = k_1^*} = -\frac{V_{k_1e}(k_1, e)}{V_{k_1k_1}(k_1, e)} \tag{18}$$

where:

$$V_{k_1e}(k_1, e) = \delta p(\gamma - \alpha) g_{k_1e}(k_1, e) + \delta \int_0^{\tilde{\beta}} p\alpha g_{k_1e}(k_1, e; \beta)) d\Phi(\beta) < 0$$

Since the two inputs k and e are substitutes we get $V_{k_1e}(k_1, e) < 0$ and then (18) is downward-sloping. This is represented by the curve HH in Figure 1.

3.5 The equilibrium

The intersection of the two best reply functions is the Nash equilibrium, denoted by N in Figure 1. We also assume that the physician's reaction function is steeper than the hospital reaction function[24]. This guarantees that the Nash equilibrium is unique and stable (Vives 1999, p. 49-52). Therefore, the following proposition holds (see Figure 1):

Proposition 1 *1) The presence of devoted physicians implies underinvestment at time $t = 1$. 2) The Nash equilibrium is not optimal since it implies a lower level of effort and investment than the First Best.*

Proof. See Appendix B ■

The first part of Proposition 1 is a straightforward application of the geometric solution of the Nash equilibrium. In Figure 1, the point $N_0 = (\hat{k}_1, 0)$ represents the benchmark solution for the case of a doctor that is not a devoted worker. In this case, the level of capital is higher than in our Nash solution $N = (k_1^*, e^*)$. To compare the Nash solution with the First Best, we need to depict the hospital iso-profit and the doctor's iso-utility curves. In Figure 1, PP represents the hospital iso-profit curve and UU the doctor iso-utility curve going through point N. The First Best is the set of points where the iso-profit and iso-utility curves are tangent. From Figure 1, it can be seen that these points are characterized by a higher level of effort and investment. This result can be interpreted as follows: the hospital can use the devotion of its medical staff to its own advantage through a delay in the investment decision, but this becomes a second-best solution for both parties. If the two actors cooperated, the level of capital and effort would be higher and ultimately the quality of health care would significantly improve.

4 Contractual rules and Nash equilibrium

In the previous section we have shown that the Nash solution is sub-optimal since it does not offer enough incentive to investment. The purchaser can, however, play an important role in correcting this market failure through the choice of the parameters of the long-term contract (4). In this section we compare the Nash equilibria for the following alternative values of the parameters of the purchasing rule:

- $\gamma > 0$ and $\alpha = 0$: the number of patients whose treatment is reimbursed in the second period depends only on the quality level at time $t = 1$;

[24] This assumption seems reasonable, since in most cases the rate of substitution between capital and effort is higher for physicians than for the hospital. In fact, physicians may have a stronger belief in being able to make up for the lack of a particular technology with their professional skills and effort.

- $\gamma = \alpha$: the number of patients whose treatment is reimbursed in the second period depends only on the quality level at time $t = 2$;

- $\gamma = 0$ $\alpha > 0$: the hospital can increase the number of patients treated in the second period (and its rewards) only if the quality increases in the second period.

It is worth noting that in the first case ($\gamma > 0$ and $\alpha = 0$) the option to delay the investment held by the hospital is neutralized. That is, even if the level of quality can be observed only ex post, asymmetry of information is ruled out. When the contract is signed, the purchaser cannot observe the level of investment in health technology and the physician's effort, but he will be able to do so before implementing the relevant part of the contract. In our model this is a sufficient deterrent to prevent the hospital and the physician cheating on their decision variables in the first period. In the second period the issue becomes irrelevant since the new investment is not considered in the decision of how many patients to send to the hospital. Since the purchasing rule affects only the hospital's objective function, changes in the Nash solution can be analysed through the comparision of the hospital's best reaction functions evaluated for different parameters of equation (4). Defining $k_1^{*\alpha=0}$, $k_1^{*\gamma=\alpha}$ and $k_1^{*\gamma=0}$ the level of capital that the hospital would obtain under the three cases examined, we can prove the following proposition:

Proposition 2 *1) For α sufficiently low, the level of capital and effort in period 1 can be ranked as follows:*

$$k_1^* > k_1^{*\gamma=\alpha} > \begin{matrix} k_1^{*\gamma=0} > 0 \\ k_1^{*\alpha=0} > 0 \end{matrix} \qquad \textit{and} \quad 0 < e^* < e^{*\gamma=\alpha} < \begin{matrix} e^{*\gamma=0} \\ e^{*\alpha=0} \end{matrix}$$

2) For α sufficiently high, the level of capital and effort in period 1 can be ranked as follows:

$$k_1^{*\alpha=0} > k_1^* > k_1^{*\gamma=\alpha} \quad \textit{and} \quad e^{*\alpha=0} < e^* < e^{*\gamma=\alpha}$$

while a Nash equilibrium for $\gamma = 0$ does not exist.

Proof. See Appendix C ■

A first important result follows from Proposition 2: the purchaser can induce the substitution of capital with effort by reducing the weight γ of the first period quality q_1 in the rule (4). That is, an increase in the ratio α/γ shifts down the hospital's best reply function (17) with respect to (18), as shown in Figure 2. As the real option theory predicts, an increase in the ratio α/γ (i.e in the weight of the option to wait α compared to the weight of investing today γ) defers the investment decision. This is a consequence of the "bad news principle of irreversible investment": a variance in health quality makes the investment return volatile with positive effect on the value of the investment. However, the net marginal benefit of waiting, arising from the avoidance of an investment in the bad state, increases. This induces delay (Bernanke, 1983). A second important result that follows from Proposition 2 is the impossibility of a global ranking in terms of substitution between capital and effort. In fact, the optimal level of investment is not maximised for $\alpha = 0$, and this contradicts the real option theory. That is, despite the disappearance of the option effect, we do not obtain a clear increase in the investment in the first period compared with k_1^* (and/or $k_1^{*\gamma=\alpha}$). Therefore, with devoted physicians, if the purchaser aims at maximising the level of quality by inducing an earlier adoption of new technology, in contrast with traditional results of the real option theory, it is not necessary to drive to zero the hospital's option to wait in order to promote investment in the first period. The parameter α influences both the expected marginal returns of the investment $G_{k_1}(k_1, e)$ and the marginal call option, $O_{k_1}(k_1, e)$. This means that its effect is countervailing since it incentivates delaying the investment, but it also increases its expected marginal return in the first period. The overall effect may lead to $V_{k_1}(k_1, e) > V_{k_1}^{\alpha=0}(k_1, e)$ and then $k_1^* > k_1^{*\alpha=0}$. This leads to the second important result of proposition 2. For any given γ, a threshold $\tilde{\alpha}$ may exist such that:

$$\begin{aligned} V_{k_1}(k_1, e) &\geq V_{k_1}^{\alpha=0}(k_1, e) \quad \text{for } \alpha \leq \tilde{\alpha} \\ V_{k_1}(k_1, e) &< V_{k_1}^{\alpha=0}(k_1, e) \quad \text{for } \alpha > \tilde{\alpha} \end{aligned}$$

If the option effect (i.e. α) is sufficiently high, the disequality may be reverted and we get $k_1^* < k_1^{*\alpha=0}$ (Appendix C).

Figure 2 about here

5 Contractual rules and total quality

As argued, the purchaser wants to maximise total quality in order to make the best treatment available for its patients. Although it cannot control hospital care quality, it can pursue its goal by influencing both the hospital investment in new technologies and the level of effort by the medical staff in the first period. This can be done by setting the parameters of the purchasing rule. In particular the following proposition holds :

Proposition 3 *Within the long-term contract between the hospital and the purchaser, the latter is able to rank the total quality at* $t = 1$ *as follows: 1) For* α *sufficiently low, we get:*

$$q_1^* > q_1^{*\gamma=\alpha} > \begin{array}{l} q_1^{*\gamma=0} > 0 \\ q_1^{*\alpha=0} > 0 \end{array}$$

2) For α *sufficiently high, the rank becomes:*

$$q_1^{*\alpha=0} > q_1^* > q_1^{*\gamma=\alpha} > q_1^{*\gamma=0} = 0$$

Proof. See Appendix D ■

The intuition for this result relies on the properties of the physician's best reply function DD. For example, in Figure 3, we can compare the total quality at N with the one at $N^{\gamma=\alpha}$. Let's consider the "isoqual" QQ that goes through N and depicts all the values of k_1 and e compatible with a given quality level. As k_1 decreases, the physician increases e along the curve DD, but if the marginal cost of the effort increases with e, this is not sufficient to keep the quality constant. Therefore, to the right of N, the isoqual QQ lies above the doctor's reply function DD, while to the left of N, it lies below DD. This implies that point $N^{\gamma=\alpha}$, which represents the Nash solution for $\gamma = \alpha$, lies on an isoqual lower than the one through N, with a reduction in the total quality. Similar results apply for $\gamma = 0$ and $\alpha = 0$. These results have important implications. In our model - as stated by the first part of Proposition 3 - if α is below a specific threshold $\widetilde{\alpha}$, total quality is higher than when the purchasing rule is based only on past investment ($\alpha = 0$). This implies that, for α sufficiently low but positive, the purchaser can increase total quality in the first period without eliminating the hospital's option value of investing in the second period. This is possible because of the existence of a substitution effect between capital and effort by devoted physicians. If $\alpha = 0$, there should be no substitution between capital and effort[25].

Figure 3 about here

>From Proposition 3, we can also compare total quality at the Nash equilibrium where the doctor values the quality, with the solution where the doctor does not.

[25] *In* Moretto and Levaggi (2004) the investment was higher when the option value to invest in the second period was set to zero (i.e. α was made equal to zero); in fact, the purchasing rule is backward-looking (since the hospital receives more patients only if it has invested in past periods) and the current level of investment i_2 is never considered.

Corollary 1 *The total quality is higher when the doctor values quality, i.e.*

$$q_1^* > q_1(\hat{k}_1, 0)$$

If the doctor is not devoted, he sets $e = 0$ (i.e. his effort is only e_l) and the hospital sets the investment at $(\hat{k}_1, 0)$, where the reply function intersects the vertical axis. To compare the total quality at N with the one at $(\hat{k}_1, 0)$ we consider the *isoqual* that goes through $(\hat{k}_1, 0)$, i.e. the curve $\hat{Q}\hat{Q}$ in Figure 3. Since the marginal rate of transformation between k_1 and e is decreasing, the isoqual through point $(\hat{k}_1, 0)$ lies below the curve of the hospital's reply function HH. That is, the hospital may respond optimally to an increase in the effort made by the physician by reducing the investment less than the reduction required by the isoqual through point $(\hat{k}_1, 0)$. Therefore, point N lies on an isoqual higher than the one through $(\hat{k}_1, 0)$. If the physician is not devoted, the purchaser is not able to influence the trade-off between effort and capital, hence it is indifferent between a purchasing rule defined on quality or on the level of capital. Its purchasing rule can be written as:

$$x_2(k_1, k_2) \equiv x + \gamma k_1 + \alpha(k_2 - k_1) \quad \text{with } \gamma, \alpha \geq 0 \text{ and } \gamma \geq \alpha$$

In this case, it is possible to show that the only possible rank is: $k_1^{*\alpha=0} > k_1^* > k_1^{*\gamma=\alpha} > k_1^{*\gamma=0}$as in Levaggi and Moretto (2004). In a context where the physicians are not devoted, the purchaser faces an intertemporal trade-off in deciding the level of investment, i.e. it might decide to delay hospital investment in new technology for policy reasons or due to lack of funds, but by doing so it faces the cost of verifying hospital care quality (i.e. it can verify quality only ex-post). In this case the problem offers a simple solution: setting $\alpha = 0$ in the purchasing rule allows maximisation of the level of investment at $t = 1$ and rules out any verifiability problem. With the presence of devoted doctors, on the other hand, a true trade-off exists between the level and verifiability of quality. The devoted worker adds an important dimension to the purchaser's set of choices. Besides the intertemporal substitution between present and future investment, it becomes possible to substitute capital with doctor's effort to increase current total quality. In this way, it is possible to obtain higher quality even with a lower investment in new technology, but $\alpha = 0$ is no longer sufficient to rule out the verifiability problem.

6 Conclusions

The model presented in this paper adds important new dimensions to the debate on quality and technological investment in hospital care. By considering the interaction between three actors (a purchaser, a hospital and a representative physician), we explicitly model two fundamental determinants of hospital care quality: the effort of the medical staff and the investment in technology which has the characteristic of being irreversible. The latter had been introduced by Levaggi and Moretto (2004) while in this paper the "devoted worker" characteristics of the physicians - an aspect so far neglected in the literature - is modelled explicitly. Their utility is made to depend on the salary received and on the outcome of provided care; in this respect, hospital doctors can be considered devoted workers. This assumption has important consequences on the level of investment decided by the hospital and then on the final quality of in-patient care. We show that in the game developed between the hospital and its medical staff the presence of devoted physicians allows the hospital to reduce its investment while increasing the level of quality of provided care. We show that a purchasing rule that cancels out the option to defer the decision to invest (i.e. $\alpha = 0$, where the purchaser reimburses the hospital only on the current level of quality) is not an optimal strategy to increase the total level of quality of care through a faster adoption of new technology by the hospital. From a policy perspective, this result has an important implication: in the definition of the long-term contract between the purchaser and the hospital, there is a trade-off between the level and the verifiability of quality. The purchaser could use the substitutability between capital and doctors' efforts to increase quality, but this reduces its ability to verify it. The assumption of devoted physicians also adds new dimensions to the quality setting of hospital care. In this paper we have in fact assumed that all the actors care about the same type of quality, but this assumption might be relaxed. In particular, it could be considered that the type of hospital care quality depends on the type of treatment. For surgical treatments, for example, clinical quality is probably very important, but for rehabilitation or for palliative care, relational quality might be considered more relevant. In the latter cases, the relatively higher importance of relational quality might mitigate the effect of the devoted physicians on the investment decision, hence on the optimal contractual rules. Another important extension could be the explicit consideration within the model of hospital competition on quality ruled by patients' choices. This would add another important actor (the patient) to the model and in this case the hospital's reputation would become an essential ingredient of quality.

A Proof of Lemma 1

At $t = 2$, the hospital's surplus is given by (12), i.e:

$$\begin{aligned} R^2(k_1, k_2, e; \beta) &\equiv p[x + (\gamma - \alpha)q_1(k_1, e) + \alpha q_2(k_2, e; \beta)] \\ &\equiv p[x + (\gamma - \alpha)g(k_1, e) + \alpha g(k_2, e; \beta)] \end{aligned}$$

with the properties:

$$R^2_{k_2} \equiv p\alpha \frac{\partial q_2}{\partial k_2} \equiv p\alpha g_{k_2}(k_2, e; \beta) > 0 \tag{19}$$

$$R^2_{k_2 k_2} \equiv p\alpha \frac{\partial^2 q_2}{\partial k_2^2} \equiv p\alpha g_{k_2 k_2}(k_2, e; \beta) < 0 \tag{20}$$

If the hospital does not invest in the second period, i.e. $k_2 = k_1$, its surplus (12) reduces to:

$$\begin{aligned} R^2(k_1, e; \beta) &\equiv p[x + (\gamma - \alpha)q_1(k_1, e) + \alpha q_2(k_1, e; \beta)] \\ &\equiv p[x + (\gamma - \alpha)g(k_1, e) + \alpha g(k_1, e; \beta)] \end{aligned}$$

which still depends on both q_1 and q_2[26]. Finally:

$$R^2_{k_2 \beta} \equiv p\alpha \frac{\partial^2 q_2}{\partial k_2 \partial \beta} \equiv p\alpha g_{k_2 \beta}(k_2, e; \beta) > 0 \tag{21}$$

Since the value of the hospital at $t = 1$ is:

$$V(k_1, e) \equiv R^1(k_1, e) + \delta \left\{ \int_0^{\tilde{\beta}} R^2(k_1, e; \beta) d\Phi(\beta) \right. \tag{22}$$

$$\left. + \int_{\tilde{\beta}}^{+\infty} \{ R^2(k_1, k_2(\beta), e; \beta) - r[k_2(\beta) - k_1] \} d\Phi(\beta) \right\},$$

easy computation shows that (22) can be written as:

$$V(k_1, e) \equiv R^1(k_1, e) + \delta \int_0^{+\infty} R^2(k_1, e; \beta) d\Phi(\beta) \tag{23}$$

[26] Only if $\beta = 1$ do we get $q_2 = q_1$ and

$$R^2(k_1, e; \beta) \equiv p[x + \gamma q_1(k_1, e)]$$

$$+\delta \int_{\tilde{\beta}}^{+\infty} \{-[R^2(k_1, k_2(\beta), e; \beta) - rk_2(\beta)] + [R^2(k_1, e; \beta) - rk_1]\} d\Phi(\beta).$$

where δ is the discount factor. Then, defining:

$$G(k_1, e) \equiv R^1(k_1, e) + \delta \int_0^{+\infty} R^2(k_1, e; \beta) d\Phi(\beta),$$

$$O(k_1, e) \equiv \int_{\tilde{\beta}}^{+\infty} \{-[R^2(k_1, k_2(\beta), e; \beta) - rk_2(\beta)] + [R^2(k_1, e; \beta) - rk_1]\} d\Phi(\beta),$$

by direct substitution of (7) and (12), we obtain:

$$V(k_1, e) = G(k_1, e) - \delta O(k_1, e)$$

where:

$$\begin{aligned} G(k_1, e) &\equiv px + \delta \int_0^{\infty} p[x + (\gamma - \alpha) q_1(k_1, e) + \alpha q_2(k_1, e; \beta)] d\Phi(\beta) \\ &\equiv px + \delta \int_0^{\infty} p[x + (\gamma - \alpha) g(k_1, e) + \alpha g(k_1, e; \beta)] d\Phi(\beta) \\ &\equiv px + \delta p[x + (\gamma - \alpha) g(k_1, e) + \int_0^{\infty} \alpha g(k_1, e; \beta) d\Phi(\beta)] \end{aligned}$$

$$\begin{aligned} O(k_1, e) \equiv & \int_{\tilde{\beta}}^{+\infty} \{-[p(x + (\gamma - \alpha) q_1(k_1, e) + \alpha q_2(k_2(\beta), e; \beta)) - rk_2(\beta)] \\ & + [p(x + (\gamma - \alpha) q_1(k_1, e) + \alpha q_2(k_1, e; \beta)) - rk_1]\} \, d\Phi(\beta) \\ \equiv & \int_{\tilde{\beta}}^{+\infty} \{-[p\alpha q_2(k_2(\beta), e; \beta)) - rk_2(\beta)] + [p\alpha q_2(k_1, e; \beta)) - rk_1]\} \, d\Phi(\beta) \\ \equiv & \int_{\tilde{\beta}}^{+\infty} \{-[p\alpha g(k_2(\beta), e; \beta) - rk_2(\beta)] + [p\alpha g(k_1, e; \beta) - rk_1]\} \, d\Phi(\beta) \end{aligned}$$

This concludes the proof.

B Proof of Proposition 1

The first part of the proposition is a straightforward application of the geometric solution of the Nash equilibrium. For the second part, we need to draw the hospital's iso-profit curve and the doctor's iso-utility curve in the (k_1, e) plane. Let's start with the doctor's iso-utility curve. Totally differentiating (5) we get:

$$B^1_{k_1}(k_1, e)dk_1 + B^1_e(k_1, e)de = dB^1$$

and, setting $dB^1 = 0$, we can evaluate the sign of:

$$\frac{dk_1}{de} = -\frac{B^1_e(k_1, e)}{B^1_{k_1}(k_1, e)} \tag{24}$$

The numerator is simply given by (9) while the denominator is:

$$B^1_{k_1}(k_1, e) \equiv v g_{k_1}(k_1, e) > 0$$

Then the slope of the iso-utility curve is simply determined by (9). For a fixed value of k_1,(24) is decreasing up to e^* and increasing for a higher value of e. The same procedure determines the hospital's iso-profit curve. By totally differentiating (15) we get

$$V_{k_1}(k_1, e)dk_1 + V_e(k_1, e)de = dV$$

and, then:

$$\frac{dk_1}{de} = -\frac{V_e(k_1, e)}{V_{k_1}(k_1, e)} \tag{25}$$

The numerator of (25) is simply (17) and the denumerator is given by:

$$\begin{aligned}
V_e(k_1, e) &\equiv G_e(k_1, e) - \delta O_e(k_1, e) \\
&\equiv \delta p[(\gamma - \alpha) g_e(k_1, e) + \int_0^{\infty} \alpha g_e(k_1, e; \beta) d\Phi(\beta)] \\
&\quad -\delta \int_{\tilde{\beta}}^{+\infty} \left\{ -[p\alpha g_e(k_2(\beta), e; \beta)] + [p\alpha g_e(k_1, e; \beta)] \right\} d\Phi(\beta) \\
&\equiv \delta p[(\gamma - \alpha) g_e(k_1, e) + \int_0^{\tilde{\beta}} \alpha g_e(k_1, e; \beta) d\Phi(\beta)] \\
&\quad +\delta \int_{\tilde{\beta}}^{+\infty} \left\{ p\alpha g_e(k_2(\beta), e; \beta) \right\} d\Phi(\beta)
\end{aligned}$$

Since the above expression is always positive the slope of the iso-profit curve is, for a fixed value of e,decreasing up to k_1^* and increasing for a higher value of k_1. This concludes the proof.

C Proof of Proposition 2

Since the purchasing rule affects only the hospital's objective function, to compare the Nash solutions varying the parameters of (4) we need to compare the different hospital best reaction functions. Firstly, if $\gamma = \alpha$ the purchasing rule becomes $x_2 = x + \alpha q_2$. The necessary condition for a maximum (17) becomes:

$$V_{k_1}^{\gamma=\alpha}(k_1, e) \equiv G_{k_1}^{\gamma=\alpha}(k_1, e) - \delta O_{k_1}(k_1, e) = r \tag{26}$$

where:

$$G_{k_1}^{\gamma=\alpha}(k_1, e) \equiv \delta \int_0^{+\infty} p\alpha g_{k_1}(k_1, e; \beta)) d\Phi(\beta)$$

$$O_{k_1}(k_1, e) \equiv \int_{\tilde{\beta}}^{+\infty} [p\alpha g_{k_1}(k_1, e; \beta) - r] d\Phi(\beta) \geq 0$$

and $\tilde{\beta}$ is given by (13). Since $G_{k_1}^{\gamma=\alpha}(k_1, e) < G_{k_1}(k_1, e)$ the hospital's reaction function shifts down and to the left as shown in Figure 2. Secondly, if $\gamma = 0$ and $\alpha > 0$, the purchasing rule becomes $x_2 = x + \alpha(q_2 - q_1)$, which makes the surplus $R^2(k_2, k_1, e; \beta)$ independent from q at $q_2 = q_1$. The necessary condition for a maximum (17) becomes:

$$V_{k_1}^{\gamma=0}(k_1, e) \equiv G_{k_1}^{\gamma=0}(k_1, e) - \delta O_{k_1}(k_1, e) = r \tag{27}$$

where:

$$G_{k_1}^{\gamma=0}(k_1, e) \equiv \delta \int_0^{+\infty} p\alpha [g_{k_1}(k_1, e; \beta) - g_{k_1}(k_1, e)] d\Phi(\beta)]$$

$$O_{k_1}(k_1, e) \equiv \int_{\tilde{\beta}}^{+\infty} [p\alpha g_{k_1}(k_1, e; \beta) - r] d\Phi(\beta) \geq 0$$

and $\tilde{\beta}$ is still given by (13). Since $G_{k_1}^{\gamma=0}(k_1, e) < G_{k_1}^{\gamma=\alpha}(k_1, e)$ we have another shift to the left of the hospital's reply curve as in Figure 2. Finally, if $\alpha = 0$

and $\gamma > 0$, the purchasing rule reduces to $x_2 = x + \gamma q_1$. For any given stock of q_1 inherited from period 1, the surplus at $t = 2$ is always constant, which makes $q_2(\beta) = q_1$ for all β. Then, condition (17) reduces to:

$$V_{k_1}^{\alpha=0}(k_1, e) \equiv G_{k_1}^{\alpha=0}(k_1, e) = r \tag{28}$$

where:

$$G_{k_1}^{\alpha=0}(k_1, e) \equiv \delta p \gamma g_{k_1}(k_1, e)$$
$$O_{k_1}^{\alpha=0}(k_1, e) \equiv 0$$

To compare (28) with (17), we can first rewrite $G_{k_1}(k_1, e)$ in the following form:

$$\begin{aligned} G_{k_1}(k_1, e) &\equiv \delta p[(\gamma - \alpha) g_{k_1}(k_1, e) + \int_0^{+\infty} \alpha g_{k_1}(k_1, e; \beta)) d\Phi(\beta)] \\ &= \delta p \gamma g_{k_1}(k_1, e) + \delta \int_0^{+\infty} p\alpha [g_{k_1}(k_1, e; \beta) - g_{k_1}(k_1, e)] d\Phi(\beta) \\ &= G_{k_1}^{\alpha=0}(k_1, e) + G_{k_1}^{\gamma=0}(k_1, e) \end{aligned}$$

and:

$$\begin{aligned} V_{k_1}(k_1, e) &\equiv V_{k_1}^{\alpha=0}(k_1, e) + G_{k_1}^{\gamma=0}(k_1, e) - \delta O_{k_1}^{\gamma=0}(k_1, e) \\ &\equiv V_{k_1}^{\alpha=0}(k_1, e) + V_{k_1}^{\gamma=0}(k_1, e) \end{aligned} \tag{29}$$

Therefore, if $V_{k_1}^{\gamma=0}(k_1, e) > 0$, $k_1^{\alpha=0}$ cannot be greater than k_1.Furthermore, if we specify (29) for the case in which $\alpha = \gamma$ it is easy to show that:

$$V_{k_1}^{\gamma=\alpha}(k_1, e) \equiv V_{k_1}^{\alpha=0}(k_1, e) + V_{k_1}^{\gamma=0}(k_1, e) \tag{30}$$

hence, if $V_{k_1}^{\gamma=0}(k_1, e) > 0$ we get $V_{k_1}^{\gamma=\alpha}(k_1, e) - V_{k_1}^{\alpha=0}(k_1, e) > 0$ and the first part of the proposition follows. Let's now consider the second part of the proposition. By (29) (and (30)), a necessary condition for having $k_1^{\alpha=0} > k_1^*$ is $V_{k_1}^{\gamma=0}(k_1, e) \equiv G_{k_1}^{\gamma=0}(k_1, e) - \delta O_{k_1}(k_1, e) < 0$, which in turn implies $k_1^{\gamma=0} = 0$. After some simple algebraical manipulations we obtain:

$$
\begin{aligned}
& G_{k_1}^{\gamma=0}(k_1,e) - \delta O_{k_1}(k_1,e) \qquad (31)\\
= \; & \delta[\int_0^{+\infty} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta) - \int_{\tilde{\beta}}^{+\infty} [p\alpha g_{k_1}(k_1,e;\beta) - r]d\Phi(\beta)]\\
= \; & \delta[\int_0^{\tilde{\beta}} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta) + \int_{\tilde{\beta}}^{+\infty} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta)\\
& - \int_{\tilde{\beta}}^{+\infty} [p\alpha g_{k_1}(k_1,e;\beta) - r]d\Phi(\beta)]\\
= \; & \delta[\int_0^{\tilde{\beta}} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta) + \int_{\tilde{\beta}}^{+\infty} [r - p\alpha g_{k_1}(k_1,e)]d\Phi(\beta)]\\
= \; & \delta[\int_0^{\tilde{\beta}} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta) + [r - p\alpha g_{k_1}(k_1,e)](1 - \Phi(\tilde{\beta})]\\
= \; & \delta[\int_0^{\tilde{\beta}} p\alpha[g_{k_1}(k_1,e;\beta) - g_{k_1}(k_1,e)]d\Phi(\beta) + p\alpha[g_{k_1}(k_1,e;\tilde{\beta}) - g_{k_1}(k_1,e)](1 - \Phi(\tilde{\beta})]
\end{aligned}
$$

If $\tilde{\beta} < 1$, the first and second terms of (31) are both negative which yields $G_{k_1}^{\gamma=0}(k_1,e) - \delta O_{k_1}(k_1,e) < 0$. On the contrary if $\tilde{\beta} > 1$ the second term is positive while the sign of the first term is ambiguous, and becomes positive if $\tilde{\beta} \gg 1$. Therefore, since:

$$\frac{\partial \tilde{\beta}}{\partial \alpha} = -\frac{g_k(k_1,e;\tilde{\beta})}{\alpha g_{k\beta}} < 0$$

a trigger value $\tilde{\alpha}$ may exist such that:

$$
\begin{aligned}
V_{k_1}(k_1,e) &< V_{k_1}^{\alpha=0}(k_1,e) \quad \text{for } \alpha > \tilde{\alpha}\\
V_{k_1}(k_1,e) &\geq V_{k_1}^{\alpha=0}(k_1,e) \quad \text{for } \alpha \leq \tilde{\alpha}
\end{aligned}
$$

This concludes the proof.

D Proof of Proposition 3

To prove the proposition it is sufficient to show that the isoquals that pass through the Nash equilibrium can be ranked.

Lemma 2 *The isoqual that passes through a Nash equilibrium, say N, lies above the hospital's reply function HH and below DD to the left of N and below HH and above DD to the right.*

Proof. To do this we compare the slope of the isoqual with the slope of the hospital's reply function and the slope of the doctor's reply function respectively. Let's first recall the MRT between k and e and the slope of the hospital's reaction function, i.e.:

$$MRT_{k,e} \equiv \frac{dk_1}{de}_{q=\bar{q}} = -\frac{g_e}{g_k} < 0 \tag{32}$$

$$\frac{dk_1}{de}_{|k_1=k_1^*} = -\frac{V_{k_1e}}{V_{k_1k_1}} < 0 \tag{33}$$

By (32) and (33), the slope of the isoqual is greater than the slope of the hospital's reaction function if:

$$\frac{g_e}{g_k} > \frac{V_{k_1e}}{V_{k_1k_1}} \tag{34}$$

Secondly, the condition that guarantees that the MRT is decreasing in e is:

$$\frac{\partial MRT_{k,e}}{\partial e} = -\frac{g_{ee}g_k - g_e g_{ke}}{(g_k)^2} > 0$$

or:

$$\frac{g_{ee}}{g_{ke}} > \frac{g_e}{g_k} \tag{35}$$

Putting together (34) and (35), with an MRT decreasing in e, the condition (34) becomes:

$$\frac{g_{ee}}{g_{ke}} > \frac{V_{k_1e}}{V_{k_1k_1}} \tag{36}$$

Thirdly, the condition that guarantees the stability of the Nash equilibrium (Vives 1999, p. 49-52) requires:

$$V_{k_1k_1}B^1_{ee} > V_{k_1e}B^1_{ek_1}$$

or:

$$\frac{B^1_{ee}}{B^1_{ek_1}} \equiv \frac{vg_{ee} - m''(e)}{vg_{ek}} > \frac{V_{k_1 e}}{V_{k_1 k_1}} \tag{37}$$

which is equivalent to (36) if $m'' = 0$. Therefore, if (37) holds for $m'' < 0$, (36) also holds. Finally,

$$\frac{de}{dk_1}_{|e=e^*} = -\frac{B^1_{ek_1}}{B^1_{ee}} \equiv -\frac{vg_{ek}}{vg_{ee} - m''(e)}$$

is also the inverse of the doctor's best reply function. ■

Let's consider the isoqual that passes through N. As HH shifts down (i.e. k_1 decreases) the doctor increases e along the curve DD and a new equilibrium N' is reached. By Lemma 2, however, N' lies on an isoqual lower than the one through N, with a reduction in the total quality. On the contrary if HH shifts up (i.e. k_1 increases) the doctor decreases e along the curve DD and by Lemma 2, the new Nash solution N'' lies on an isoqual higher than the one through N, with an increase in the total quality. This concludes the proof.

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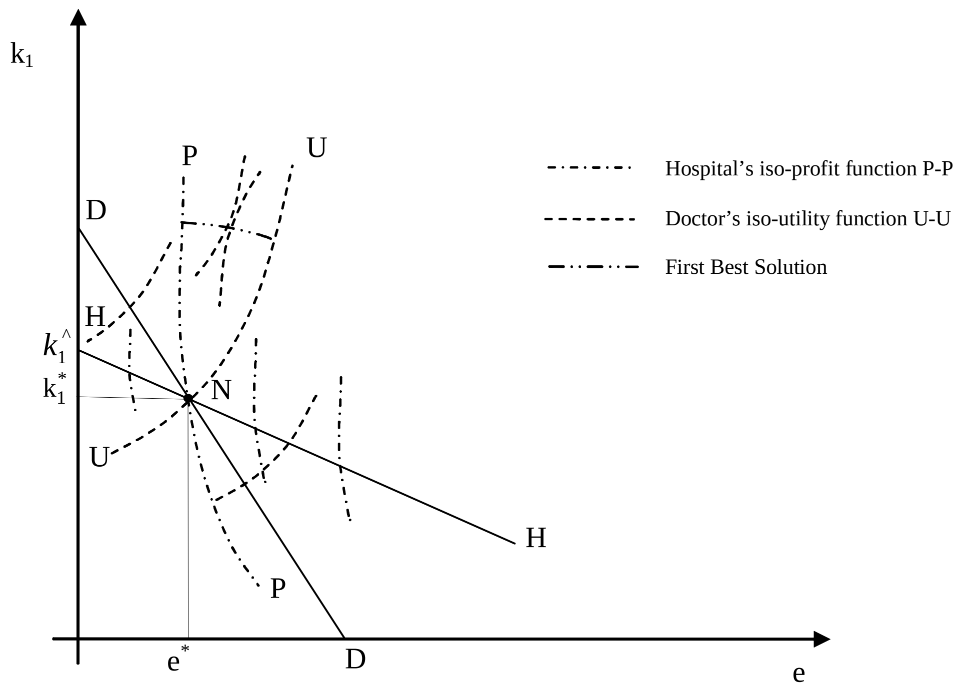
k_1
P
U
D
H
$\hat{k}_1$
k_1^*
N
U
H
P
e^*
D
e
Hospital's iso-profit function P-P
Doctor's iso-utility function U-U
First Best Solution

Figure 1

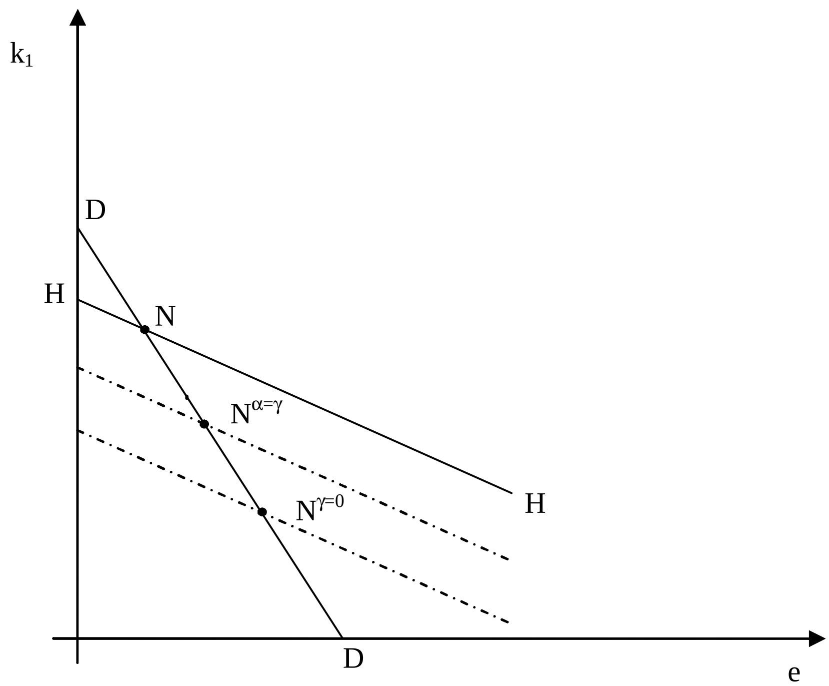

Figure 2

UNIVERSITÀ DEGLI STUDI DI PADOVA

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INVESTMENT DECISIONS IN HOSPITAL TECHNOLOGY WHEN PHYSICIAN ARE DEVOTED WORKERS

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VINCENZO REBBA
Università di Padova

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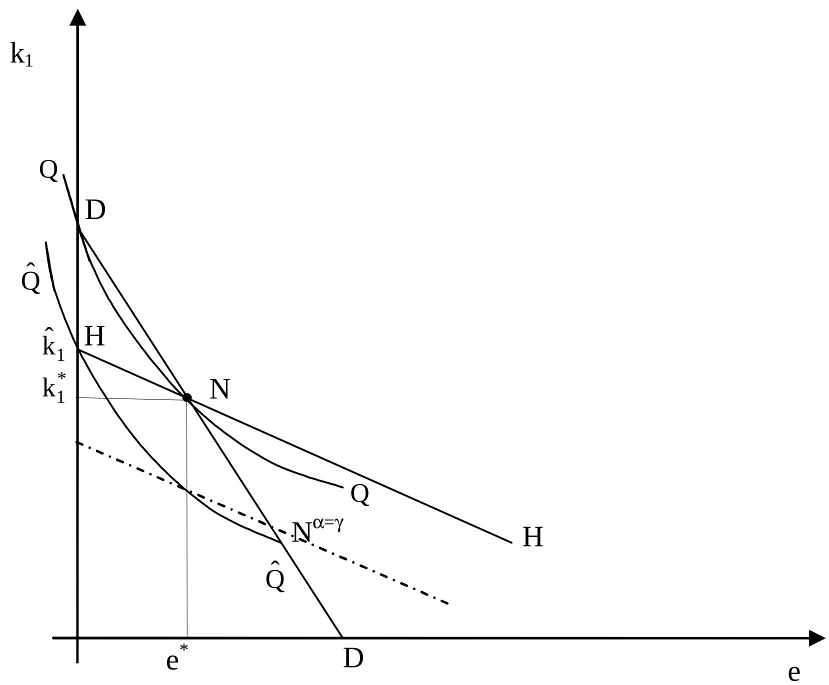

Figure 3