Readmission treatment price and product quality in the hospital sector: A note

Cellini, Roberto and Lisi, Domenico

University of Catania, Department of Economics and Business

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Readmission treatment price and product quality in the hospital sector: A note*

Roberto Cellini† Domenico Lisi‡

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Abstract

In this paper, we study the effect of readmission treatment payment in a dynamic framework characterised by competition among hospitals and sluggish beliefs of patients concerning the service quality. We find that the effect of readmission treatment payment depends on the interplay between the effect of quality in lowering readmissions and its effect on future demand. When the readmission occurrence strongly depends on the service quality, the higher the readmission treatment payment for hospitals, the lower the incentive to provide quality. Instead, when readmission depends barely on quality, the readmission payment acts as the treatment price for first admissions, and thus it reinforces the incentive to provide quality. We also show that the detrimental effect of readmission payments on quality are fed by a high degree of demand sluggishness, that is, by situation where current quality has modest effect on future demand changes. Our findings are robust to different equilibrium concepts of the differential game (i.e., open-loop and state-feedback). The results suggest that a discounted regulated price for readmission can be an effective (and cost-free) policy tool to improve healthcare quality, especially when the market is characterised by sluggish beliefs about quality.

Keywords: readmissions; hospital quality; demand sluggishness; differential game.

JEL Classification: I11; I18; C73.

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†Department of Economics and Business, University of Catania, 95129, Italy. E-mail: cellini@unict.it.

‡Department of Economics and Business, University of Catania, 95129, Italy. E-mail: domenico.lisi@unict.it.

1 Introduction

In recent years, several countries have introduced financial public incentives to improve the quality of healthcare, especially in the hospital sector, including a variety of pay-for-performance (or value-based purchasing) programmes (Busse et al., 2011; Cashin et al., 2014; Milstein and Schreyoegg, 2016). In this respect, readmission rates are among the most widely used outcome-based indicators of performance. The underlying idea is that, even if some readmissions are inevitable, a higher quality of care reduces post-discharge complications and, thus, readmissions. Examples of healthcare policies targeting hospital readmissions can be found, among others, in the US and in the UK. The US Hospital Readmission Reduction Program has introduced a penalty system for hospitals with higher readmission rates for selected medical procedures (e.g., acute myocardial infarction, hip replacement). Differently, the English NHS does not provide any payment to hospitals for readmissions within 30 days of discharge.

Despite this increasing use in healthcare policy, only few recent theoretical papers analyse the effect of financial incentives linked to readmissions. Lisi et al. (2018) study a model of hospital competition under a pay-for-performance programme which rewards lower mortality and/or readmission rates: they show that readmission rates are affected by different types of selection bias, and this might lead to counterproductive effects that can weaken the hospitals' incentive to provide quality. Guccio et al. (2016) analyse the role of readmission payment in a static framework where a monopolistic hospital provides healthcare treatments, and chooses quality under different payment regimes: they find that a higher readmission payment unambiguously reduces quality.[1] They also emphasise the role of readmission payment as an instrument to extract the hospital's profit.

In this paper, we study the effect of readmission treatment payment in a dynamic framework characterised by sluggish beliefs of patients concerning quality. In a similar framework, Brekke et al. (2012) and Siciliani et al. (2013) show that demand sluggishness in regulated markets where providers compete on quality −as, specifically, the healthcare market− reduces the incentives to provide quality.

Here, we show that, once dynamic strategic interaction among hospitals is taken into account, the effect of readmission payment policy on the quality of care depends on the strength with which

[1] The links between competition, efficiency and quality provision in hospital sector are investigated by a large body of theoretical and empirical literature. See, e.g., Bisceglia et al. (2018), Brekke et al. (2010, 2014), Levaggi et al. (2012), just to mention a few contributions that could be easily reinterpreted by explicitely considering re-admission payment as a tool to affect hospitals' quality provision.

quality changes affect future demand. Specifically, we show that a higher readmission payment reduces the hospitals' incentive to provide quality, if the effect of quality in lowering readmissions is higher than the effect of quality in increasing future demand. Most importantly, we show that a higher demand sluggishness increases the scope for the readmission payment being detrimental to quality. Therefore, as a policy implication, our results suggest that, when the healthcare market is characterised by sluggish beliefs about quality, a lower readmission payment might represent an easy (and cost-free) policy instrument to counterbalance the perverse effect of demand sluggishness in the market.

The paper is organised as follows. In Section 2, we present the basics of the dynamic model, largely borrowed from the differential game presented by Brekke et al. (2012), and focus on the introduction of a specific readmission payment policy. In Section 3, we characterise the equilibrium of the game, focussing on the effect of readmission payment in steady-state quality, under the open-loop solution concept. The features of the equilibrium under a different solution concept (the closed-loop state-feedback solution) are presented in Section 4 (and fully developed in Appendix). Section 5 concludes the paper.

2 Model

Following a well established literature line (e.g., Beitia, 2003; Brekke et al., 2011), we consider a market for medical treatment *à la* Hotelling (1929) with two hospitals located (exogenously) at either end of the unit line $S = [0, 1]$. On the line segment S there is a uniform distribution of patients, with density normalized to 1, each demanding one medical treatment. The utility of a patient who is located at $x \in S$ and receiving treatment from hospital i, located at z_i, is given by

$$U(x, z_i) = v + kq_i - \tau |x - z_i| \tag{1}$$

where v is the gross valuation from medical treatment, $q_i \geq \underline{q}$ is the quality of treatment at hospital i, and τ is the marginal disutility of travelling. The parameter k measures the marginal utility of quality. The lower bound $\underline{q}$ is the minimum quality standard the hospitals are allowed to offer and is, for simplicity, set equal to 0, so that $q_i < \underline{q} = 0$ can be interpreted as malpractice.

The patient who is indifferent between hospital i and j is located at D^*, with

$$v + kq_i - \tau D^* = v + kq_j - \tau \left(1 - D^*\right). \tag{2}$$

Hence, the *potential demand* for hospital i is

$$D^* = \frac{1}{2} + \frac{k\left(q_i - q_j\right)}{2\tau} \tag{3}$$

implying that the hospital with a higher quality has a potential demand in excess of $\frac{1}{2}$. The extent to which the difference in quality affects the market share depends on the marginal disutility of travelling relative to quality $\frac{\tau}{k}$, with a higher $\frac{\tau}{k}$ making demand less responsive to change in quality.

Healthcare demand is assumed to be characterised by sluggish beliefs about quality (Brekke et al., 2012; Siciliani et al., 2013), which can be due to imperfect information about quality but also to personal and familiar habits, typical in the demand side of the healthcare market. This implies that changes in quality do not translate instantaneously into demand changes: we assume that, at each point in time, only a fraction $\gamma \in [0,1]$ of patients become aware of changes in quality and change their patronised provider. The law of motion of *actual demand* $D(t)$ of hospital i, as opposed to *potential demand* $D^*(t)$, is thus given by

$$\frac{dD(t)}{dt} \equiv \dot{D}(t) = \gamma\left(D^*(t) - D(t)\right). \tag{4}$$

The lower is γ, the less actual demand responds to quality changes. Therefore, γ is an inverse measure of the degree of sluggishness in patients' beliefs about quality. Since total demand is inelastic and constant over time, the law of motion of the actual demand of hospital j is then given by

$$\frac{d\left[1 - D(t)\right]}{dt} = \gamma\left[\left(1 - D^*(t)\right) - \left(1 - D(t)\right)\right] \tag{5}$$

which can be easily rearranged as (4). $D(t)$ and $D^*(t)$ have to be interpreted respectively as the "first admission" actual and potential demand (also called the "index admission" in the context of readmissions), that is, the demand for the treatment of a disease when it occurs.

The instantaneous cost of provision is given by a fixed cost F and a variable cost $C(\cdot)$ increasing and convex in output D and quality q_i. Specifically, we assume that $C(\cdot)$ takes the following quadratic form:

$$C(D(t), q_i(t)) = \frac{\theta}{2}q_i^2 + \frac{\beta}{2}D^2 \tag{6}$$

with $\theta > 0$ and $\beta > 0$. Hospitals receive (from a thrid part) a unit price p for each patient treated. As usual in this framework, to ensure positive levels of quality in equilibrium, we assume that $p > \frac{\beta}{2}$.

Let us underline that $D(\cdot)$ and $C(\cdot)$ refer to the first-admission for the patient case treatment. The novelty of the present model rests on the explicit consideration of readmission of treated patients. We assume that each patient treated by hospital i has a probability R of being readmitted for the treatment of the same (or related) disease.[2] R can be interpreted as the fraction of patients who need re-admission. It makes sense to assume that this fraction (or, equivalently, the probability of being readmitted for each patient) depends on the quality offered by hospital i. This means that $0 \leq R(q_i) \leq 1$ and $\partial R/\partial q_i < 0$. For simplicity, we assume that $R(\cdot)$ takes the following form:

$$R(q_i) = \max\{1 - \delta q_i, 0\} \tag{7}$$

where $\delta > 0$ is the marginal effect of quality upon the probability of readmission. Although (7) is a simplifying assumption, it has the advantage of keeping the model tractable while still having a clear interpretation of the readmission "quality dependence".[3,4] Of course, (7) entails parametric restrictions on δ such that $0 \leq 1 - \delta q \leq 1$; below, we show that in this model, in front of sensible assumptions, such parametric restrictions are not binding in steady state.

Then, whenever a patient is readmitted hospitals incur a readmission cost r, assumed to be somewhat smaller than the marginal cost at the initial admission. This assumption on r should capture the fact that patients readmitted usually do not need to repeat all medical procedures performed at the first admission, and their conditions are already known in the hospital. On the

[2] Available empirical evidence shows that the great majority (on average, around 85-90%) of patients needing readmission are readmitted to the same hospital where they received the first treatment (see, e.g., Staples et al., 2014; Tsai et al., 2015; McAlister et al., 2017). Therefore, for the sake of simplicity, readmission here is intended as the readmission to the same hospital. Nonetheless, our main conclusions would not be qualitatively affected by explicitly considering that a small fraction of patients needing readmission may be re-treated by the other hospital.

[3] In fact, modelling the readmission probability as a non-linear function bounded in the domain $[0, 1]$ would make the following analysis intractable.

[4] Notice that this form of readmission probability allows us to have a more general interpretation of the utility of patients, as represented by eq. (1). In particular, suppose that patients suffer a disutility η in case they are readmitted and, furthermore, they know it happens with probability (7). Then, the expected utility of a patient who is located at $x \in S$ and receiving treatment from hospital i, located at z_i, is given by $E[U(x, z_i)] = v + kq_i - \eta(1 - \delta q_i) - \tau|x - z_i|$, which can be written as (1) with $\tilde{v} = v - \eta$ and $\tilde{k} = k + \eta\delta$. Therefore, we can interpret the parameter k as the expected marginal utility of quality.

other hand, hospitals receive a payment λp, with $\lambda \in [0,1]$. When $\lambda = 1$, hospitals receive a full price p, as for the first admission; when $\lambda = 0$ instead, hospitals receive nothing and, thus, suffer the readmission cost. Therefore, $(\lambda p - r)$ represents the profit margin from a readmitted patient, and $(\lambda p - r) D(t) R(q_i)$ can be interpreted as the expected profit from readmissions. Note that the nature of the cost function associated to readmission treatments is different from the cost associated to first treatments. In particular, the cost function of readimitted patients is linear in quantity. This assumption not only obeys reasons of analytical convenience,[5] but it is intended to underline that readmission has a truly different nature as compared to first admission (readmission has simply to adjust or to complement the previous treatment).

We assume that each hospital maximizes the present value of its expected profit, which also includes the potential profit from readmitted patients. Specifically, the instantaneous expected profit of hospital i is given by

$$E[\pi_i(t)] = pD(t) - C(D(t), q_i(t)) - F + (\lambda p - r) D(t) R(q_i) \tag{8}$$

and the problem of hospital i (defining ρ as the rate of time preference) can be outlined as follows:

$$\underset{q_i}{Maximize} \int_0^{+\infty} E[\pi_i(t)] e^{-\rho t} dt$$

subject to

$$\dot{D}(t) = \gamma (D^*(t) - D(t)) \tag{9}$$

$$D(0) = D_0 > 0 \tag{10}$$

where q_i is the control variable.

We are in front of a differential game.[6] In what follows, we characterise the Nash equilibrium, assuming an *open-loop* information structure. Under this information structure, players choose the optimal plan at the beginning of the game, knowing the initial state of the system (i.e. $D(0) = D_0$), and then stick to it forever (i.e. $q_i^{OL} = f(t)$). Then, we find the *state-feedback solution*[7] (with

[5] Quadratic cost function for readmission treatments would lead to a cubic objective function.

[6] Basar and Olsder (1995), Dockner et al. (2001), Basar and Zaccour (2018) are reference books for differential games.

[7] We borrow the label from Basar et al. (2018); state-feedback solution is also known as closed-loop feedback solution. For a deeper discussion of the solution concepts of differential games see also Cellini and Lambertini (2004). Brekke et al. (2012) discuss the different solution concepts in a specific application to health economics.

analytical details available in Appendix). Under this solution concept, players observe the value of the state variable in each period of time (i.e. $D(t)$), and set the optimal choice in each period of time, depending on the current value of the state variable (i.e. $q_i^{SF} = f(D(t))$).

3 Open-Loop solution

The current-value Hamiltonian associated with the maximization problem is:

$$H_i = pD - \frac{\theta}{2}q_i^2 - \frac{\beta}{2}D^2 - F + (\lambda p - r)D(1 - \delta q_i) + \mu_i\gamma\left(\frac{1}{2} + \frac{k(q_i - q_j)}{2\tau} - D(t)\right) \tag{11}$$

where μ_i is the current-value co-state variable associated with the state equation. The open-loop solution satisfies:

$$\frac{\partial H_i}{\partial q_i} = -\theta q_i - (\lambda p - r)D\delta + \mu_i\frac{\gamma k}{2\tau} = 0 \tag{12}$$

$$\dot{\mu}_i = \rho\mu_i - \frac{\partial H_i}{\partial D} = (\rho + \gamma)\mu_i - [p + (\lambda p - r)(1 - \delta q_i) - \beta D] \tag{13}$$

$$\dot{D} = \frac{\partial H_i}{\partial \mu_i} = \gamma\left(\frac{1}{2} + \frac{k(q_i - q_j)}{2\tau} - D(t)\right) \tag{14}$$

to be considered along with the transversality condition $\lim_{t\to+\infty} e^{-\rho t}\mu_i(t)D(t) = 0$.[8]

By differentiating (12) with respect to time, substituting $\dot{\mu}_i$ with (13) and $\dot{D}$ with (14), we obtain

$$\dot{q}_i = (\rho + \gamma)q_i + \frac{\delta\gamma k}{2\tau\theta}(\lambda p - r)q_j + \left[(\lambda p - r)\frac{\delta(\rho + 2\gamma)}{\theta} + \frac{\gamma k\beta}{2\tau\theta}\right]D - \frac{\gamma k}{2\tau\theta}\left[p + (\lambda p - r)\left(1 + \frac{\tau\delta}{k}\right)\right] \tag{15}$$

which, along with (14), describe the dynamics of the system. Specifically, the dynamics around the steady-state, with symmetric qualities, can be represented in matrix form as follows:

$$\begin{bmatrix}\dot{q}(t)\\ \dot{D}(t)\end{bmatrix} = \begin{bmatrix}(\rho+\gamma) + \frac{\delta\gamma k}{2\tau\theta}(\lambda p - r) & (\lambda p - r)\frac{\delta(\rho+2\gamma)}{\theta} + \frac{\gamma k\beta}{2\tau\theta}\\ 0 & -\gamma\end{bmatrix}\begin{bmatrix}q(t)\\ D(t)\end{bmatrix} + \begin{bmatrix}-\frac{\gamma k}{2\tau\theta}\left(p + (\lambda p - r)\left(1 + \frac{\tau\delta}{k}\right)\right)\\ \frac{\gamma}{2}\end{bmatrix} \tag{16}$$

where the 2-by-2 matrix is the Jacobian J of the dynamic system. It is straightforward to see from J that the equilibrium is stable in the saddle-path sense, i.e., there is only one admissible path

[8] In order to meet the second-order condition, it is sufficient that the Hamiltonian is concave in the control and the state variables: $H_{q_iq_i} = -\theta < 0$, $H_{DD} = -\beta < 0$, $H_{q_iq_i}H_{DD} > (H_{Dq_i})^2$ or $\theta\beta > (\lambda p - r)^2\delta^2$ which is satisfied if the cost function is sufficiently convex.

leading to the steady-state.[9]

3.1 Steady-state quality and readmission payment

The steady-state level of quality, i.e. $\dot{q} = 0$ and $D = \frac{1}{2}$, is given by

$$q^{OL} = \frac{\left(p - \frac{\beta}{2}\right) k - (\lambda p - r) \left[\tau\delta\left(1 + \frac{\rho}{\gamma}\right) - k\right]}{2\tau\theta\left(1 + \frac{\rho}{\gamma}\right) + (\lambda p - r)\,\delta k}. \tag{17}$$

Also in the present model, like in Brekke et al. (2012), the comparative statics of (17) with respect to γ unambiguously shows that a higher degree of sluggishness in patients' beliefs about quality reduces steady-state quality:

$$\frac{\partial q^{OL}}{\partial \gamma} = \frac{k\tau\rho\left[\left(p - \frac{\beta}{2}\right) 2\theta + (\lambda p - r)\,2\theta + (\lambda p - r)^2 \delta^2\right]}{\left[2\tau\theta\,(\rho + \gamma) + (\lambda p - r)\,\delta k\gamma\right]^2} > 0. \tag{18}$$

Furthermore, a higher marginal cost of quality (θ), a higher marginal cost of output (β) and a higher rate of time preference (ρ) reduce steady-state quality.[10]

More interestingly, the comparative statics with respect to the readmission payment (λ) yields

$$\frac{\partial q^{OL}}{\partial \lambda} = -pk\frac{\left[\frac{\tau}{k}\delta\left(1 + \frac{\rho}{\gamma}\right) - 1\right] 2\tau\theta\left(1 + \frac{\rho}{\gamma}\right) + \left(p - \frac{\beta}{2}\right) k\delta}{\left[2\tau\theta\left(1 + \frac{\rho}{\gamma}\right) + (\lambda p - r)\,\delta k\right]^2}. \tag{19}$$

From (19), it can be seen that $\partial q^{OL}/\partial \lambda$ is not unambiguously negative, as one might expect. Specifically, the term which determines the effect of λ upon the steady-state quality is $\left[\frac{\tau}{k}\delta\left(1 + \frac{\rho}{\gamma}\right) - 1\right]$,

[9] Specifically, the Jacobian in (16) has two eigenvalues $\lambda_1 = (\rho + \gamma) + \frac{\delta\gamma k}{2\tau\theta}(\lambda p - r) > 0$ and $\lambda_2 = -\gamma < 0$, with $tr\,(J) = \rho + \frac{\delta\gamma k}{2\tau\theta}(\lambda p - r) > 0$ and $\det(J) = -\gamma\left[(\rho + \gamma) + \frac{\delta\gamma k}{2\tau\theta}(\lambda p - r)\right] < 0$.

[10] It is also easy to show that, as in Brekke et al. (2012), the $\lim_{\gamma \to 1, \rho \to 0} q^{OL}$ is equal to the Nash equilibrium quality in a corresponding static model where D is equal to (3).

and in particular $\partial q^{OL}/\partial\lambda < 0$ if $\left[\frac{\tau}{k}\delta\left(1+\frac{\rho}{\gamma}\right)-1\right] > 0$; more conveniently:[11]

$$\frac{\partial q^{OL}}{\partial\lambda} < 0 \quad if \quad \delta > \frac{k}{\tau}\left(\frac{1}{1+\frac{\rho}{\gamma}}\right). \tag{20}$$

Notice that δ is the expected marginal cost (benefit) of increasing (decreasing) quality in term of lower (higher) expected readmissions. Moreover, $\frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)$ can be interpreted as the discounted marginal benefit (cost) of increasing (decreasing) quality in term of higher (lower) future demand. Therefore, condition (20) simply states that if the expected marginal cost of increasing quality is higher than the discounted marginal benefit of doing so, then a higher readmission payment represents an incentive for hospitals to lowering quality.[12] These results can be summarised by the following:

Proposition 1 *The effect of a higher readmission payment* (λ) *on steady-state quality is not unambiguous. If the marginal effect of quality in lowering readmission probability* (δ) *is higher than the discounted marginal effect of quality in increasing future demand* $\left(\frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)\right)$, *then a higher readmission payment* (λ) *reduces steady-state quality.*

The intuition for this result is clear: if hospitals received a high payment for patients readmitted (jointly with a sufficiently small effect of quality upon future demand), a (perverse) incentive would operate to reduce quality in order to increase readmissions (i.e. $\frac{\partial q^{OL}}{\partial\lambda} < 0$). On the other hand, if readmissions depend barely on quality (i.e. δ is sufficiently small)[13], a higher λ acts just as a higher p, since it increases the expected revenue from future patients and, thus, provides an incentive to increase quality in order to attract more future patients (i.e. $\frac{\partial q^{OL}}{\partial\lambda} > 0$). Therefore, in this latter case there is no reason for healthcare policy to reduce readmission payment.

[11] From (17), it can be seen that the steady-state quality q^{OL} is positive so long as $\delta < \left[\frac{(\lambda p-r)+\left(p-\frac{\beta}{2}\right)}{(\lambda p-r)}\right]\frac{k}{\tau}\left(\frac{1}{1+\frac{\rho}{\gamma}}\right)$. Since $\left[\frac{(\lambda p-r)+\left(p-\frac{\beta}{2}\right)}{(\lambda p-r)}\right] > 1$, the condition (20) is consistent with a positive steady-state quality, which also guarantees that $1-\delta q^{OL} < 1$. Furthermore, when $\delta = \frac{k}{\tau}\left(\frac{1}{1+\frac{\rho}{\gamma}}\right)$, it can be seen that $1-\delta q^{OL} > 0$. To see this, notice that $1-\delta q^{OL} > 0$ requires that $(\lambda p - r) - \left(p-\frac{\beta}{2}\right) > -2\theta\left[\frac{\tau}{k}\left(1+\frac{\rho}{\gamma}\right)\right]^2$, which is guaranteed by the assumption on marginal treatment costs.

[12] Notice that $\delta > \frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)$ is a sufficient but not necessary condition for $\frac{\partial q^{OL}}{\partial\lambda} < 0$. In fact, from (19) it can be easily seen that the necessary condition for $\frac{\partial q^{OL}}{\partial\lambda} < 0$ is $\delta > \frac{1}{\frac{\tau}{k}\left(1+\frac{\rho}{\gamma}\right)+\frac{(p-\beta/2)}{2\theta}\frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)}$, which is clearly less stringent than $\delta > \frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)$.

[13] More specifically, $\frac{\partial q^{OL}}{\partial\lambda} > 0$ so long as $\delta < \frac{1}{\frac{\tau}{k}\left(1+\frac{\rho}{\gamma}\right)+\frac{(p-\beta/2)}{2\theta}\frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)}$, which is strictly positive and fully consistent with a positive steady-state quality (see the condition in footnote 10).

Finally, it can be seen that a higher demand sluggishness (i.e., a lower γ) increases, *ceteris paribus*, the scope for λ reducing steady-state quality. Let us define $\bar{\delta} = \frac{k}{\tau}\left(\frac{1}{1+\rho/\gamma}\right)$, i.e. $\bar{\delta}$ is the smallest marginal effect of quality in the probability of readmission, sufficient to guarantee that $\frac{\partial q^{OL}}{\partial \lambda} \leq 0$. The interplay between demand sluggishness and readmission payment is summarised in the following:

Proposition 2 *A higher degree of demand sluggishness (the inverse of γ) in the healthcare market reduces the smallest marginal effect of quality in the probability of readmission $\left(\bar{\delta}\right)$ sufficient to guarantee that a higher readmission payment (λ) reduces steady-state quality and, thus, increases the scope for being the readmission payment (λ) detrimental to quality.*

The intuition for this result is that, when demand is sluggish, hospitals do not expect to bear a significant cost (in term of lower future demand) from lowering quality. Thus, in this context, readmissions may become an attractive source of revenue, and -cynically enough, admittedly- even a small effect of quality in reducing readmissions might restrain hospitals from providing higher quality.

Therefore, when the healthcare market is characterised by sluggish beliefs about quality, there are at least two reasons for regulators (policy-makers) to reduce readmission payment and, in particular, to avoid providing a full readmission payment (i.e. $\lambda = 1$). First, if demand is sluggish, it is more likely that a full readmission payment provides a perverse incentive for quality provision; instead, a lower readmission payment might crowd-out this financial incentive. This is the case, for instance, with $\lambda = \frac{r}{p}$ for which the profit margin from readmitted patients is exactly neutralized. Second, when the demand is sluggish, hospitals have low incentives to provide a high quality of healthcare services because they do not expect to get a significant benefit in term of higher future demand. In this context, a lower readmission payment might represent an easy and cost-free policy instrument to counterbalance the demand sluggishness in the market. In this respect, notice also that, if the degree of demand sluggishness is high (i.e. γ is low), the usual price instrument p is less effective in stimulating quality, beyond being not cost-free.

4 State-Feedback solution

The open-loop solution is appropriate when players set their plans at the beginning of time, and the pattern of choice variables only depends on time. Players have to use open-loop solution if they cannot observe the dynamic evolution of the state of the world, or they have to commit to a plan. An alternative solution, widely considered by literature, is the state-feedback solution, in which players' control variables depend on current state variable(s). It is easy to obtain this type of solution in problems with a linear-quadratic structure, like in the present case, guessing a quadratic form of the value functions and a linear form for the control variable of each player, obeying the Bellman equation.

In the presence of readmissions, the substantial solution of the model turns out to be similar as in Brekke et al. (2012), apart from different coefficients in the linear equation describing the equilibrium solution for the choice variables. Also the properties of the steady-state are the same, apart from different parametric conditions assuring the full stability of the dynamic system. The detailed calculations for the state-feedback solution are provided in the Appendix. Specifically, the state-feedback decision rules are given by:

$$q_i = \phi_i(D) = \frac{\gamma k}{2\tau\theta}\left[\alpha_1 + \left(\alpha_2 - \frac{2(\lambda p - r)\delta\tau}{\gamma k}\right)D\right] \tag{21}$$

$$q_j = \phi_j(D) = \frac{\gamma k}{2\tau\theta}\left[\alpha_1 + \left(\alpha_2 - \frac{2(\lambda p - r)\delta\tau}{\gamma k}\right)(1-D)\right] \tag{22}$$

where

$$\alpha_1 = \frac{p + (\lambda p - r) + \frac{\gamma\alpha_2}{2}\left[1 - \frac{\gamma k^2}{2\theta\tau^2}\left(\alpha_2 - \frac{2(\lambda p - r)\delta\tau}{\gamma k}\right)\right]}{\gamma + \rho - \frac{\gamma^2 k^2}{4\theta\tau^2}\left(\alpha_2 - \frac{4(\lambda p - r)\delta\tau}{\gamma k}\right)} > 0 \tag{23}$$

$$\alpha_2 = -\frac{2\theta\tau^2\left(\psi - 2\gamma - \rho - \frac{\gamma k}{\theta\tau}2(\lambda p - r)\delta\right)}{3\gamma^2 k^2} < 0 \tag{24}$$

and

$$\psi := \sqrt{\left(2\gamma + \rho + \frac{\gamma k}{\theta\tau}2(\lambda p - r)\delta\right)^2 + \frac{3\gamma^2 k^2}{\theta^2\tau^2}\left(\theta\beta - (\lambda p - r)^2\delta^2\right)}.^{14} \tag{25}$$

The corresponding steady-state quality is obtained by applying the steady-state condition $D = \frac{1}{2}$

[14] Notice that the concavity condition of the value function requires that $\theta\beta > (\lambda p - r)^2\delta^2$, which is the same condition we found for the concavity of the Hamiltonian in the open-loop solution.

to (21) and (22). The comparative statics with respect to the readmission payment (λ) yields

$$\begin{aligned}\frac{\partial q^{SF}}{\partial \lambda} &= \frac{\gamma k}{2\tau\theta}\left\{\frac{p\left(1+\frac{\gamma k\delta}{2\theta\tau}\alpha_2\right)-\frac{\gamma k\delta}{\theta\tau}p\alpha_1}{\gamma+\rho-\frac{\gamma^2k^2}{4\theta\tau^2}\left(\alpha_2-\frac{4(\lambda p-r)\delta\tau}{\gamma k}\right)}\right\} \\ &\quad -p\frac{\delta}{2\theta}\left\{1+\frac{2}{3}\left[\frac{\left(2\gamma+\rho+\frac{\gamma k}{\theta\tau}2\left(\lambda p-r\right)\delta\right)-\frac{3\gamma k}{2\theta\tau}\left(\lambda p-r\right)\delta}{\psi}-1\right]\right\}. \end{aligned} \qquad (26)$$

The second term in (26) is unambiguously negative, as the expression in the square brackets, although negative, is strictly included between zero and one in absolute value. Therefore, the sign of (26) depends on the first term. In particular, it is easy to see that $\left(1+\frac{\gamma k\delta}{2\theta\tau}\alpha_2\right)<0$ is sufficient condition for having $\partial q^{SF}/\partial\lambda<0$; put in a different, more convenient, way:

$$\frac{\partial q^{SF}}{\partial \lambda}<0 \quad if \quad \delta>\frac{3\gamma k}{\tau\left(\psi-2\gamma-\rho-\frac{\gamma k}{\theta\tau}2\left(\lambda p-r\right)\delta\right)}. \qquad (27)$$

The condition assuring $\frac{\partial q^{SF}}{\partial \lambda}<0$ is more cumbersome in the case of the state-feedback solution as compared to the open-loop solution. This is not surprising, as long as the effect of quality changes on future demand is less trivial under the state-feedback information structure, due to the intertemporal strategic interaction among players. From (27), however, we can see that the underlying economic factors at work are similar to (20). Overall, we can see that also in the state-feedback solution the effect of the readmission payment (λ) is not unambiguous, and it depends on the interplay between the characteristics of the healthcare market (such as, the degree of demand sluggishness) and the marginal effect of quality in lowering readmission probability.

5 Concluding remarks

We have revisited the dynamic model of quality competition among healthcare providers – let us think of hospitals – by explicitly modelling the case of readmission. Healthcare services are characterised by specific features, including asymmetric information and demand sluggishness, which make competition among providers and market regulation peculiar in this sector. In the present study, we have focussed on the role played by the regulated price associated to readmitted patients. We have shown, in a differential game framework, that a discounted regulated price associated to readmission treatment can be an effective (and cost-free) policy tool to improve healthcare quality.

However, its effectiveness depends also on the characteristics of the healthcare market. In particular, we have found that, in front of a sluggish demand, it is more likely that a full readmission payment provides a perverse incentive for quality provision. In this context, a discounted readmission payment might crowd-out this perverse financial incentive. We have also shown that the effect of readmission payment is not equal across medical treatments, but it plays a major role in treatments where readmissions are more "quality dependent". Our results are robust to different assumptions concerning the information sets of players, that is, they hold under both the open-loop and the state-feedback Nash equilibrium of the differential game.

In recent times, different countries have adopted policy measures providing a discounted (if not null, such as in the UK and Germany) regulated price for readmissions. The theoretical model presented in this paper supports this choice, but at the same time it makes clear that the effectiveness of a reduced readmission payment policy in stimulating the quality of care is conditioned by several factors, even in a very simplified theoretical framework. In this respect, our theoretical model can contribute to the literature dealing with the links among competition, efficiency and quality provision in the hospital sector: it makes clear, once again, that the relations are far from being clear-cut, and several factors interact in determining the final effects of competition and incentives upon quality provision.[15] With specific reference to readmission payment as a policy tool, we have shown that there is no reason for healthcare policy to reduce readmission payment for medical treatments where readmissions depend barely on quality. Our results can have also implications for the empirical investigation of the effect of readmission payment policy; in particular, our results suggest that readmission policy should be more effective in medical sectors where readmissions are more sensitive to quality and where demand is more sluggish.

References

[1] Basar, T., Olsder, G.J. (1995), *Dynamic Noncooperative Game Theory*, San Diego, Academic Press.

[2] Basar, T., Haurie, A., Zaccour, G. (2018), "Nonzero-Sum Differential Games", in: Basar, T., and Zaccour, G. (Eds.), *cit.*.

[3] Basar, T., and Zaccour, G. (Eds.), *Handbook of Dynamic Game Theory*, Berlin, Springer.

[15] Limiting our attentio to very recent contributions, see, e.g., Cellini et al. (2018) for a theoretical investigation, and Longo et al. (2019) for an applied analysis.

[4] Beitia, A. (2003), "Hospital quality choice and market structure in a regulated duopoly", *Journal of Health Economics* 22: 1011–1036.

[5] Bisceglia, M., Cellini, R., Grill,i L (2018), "Regional regulators in healthcare service under quality competition: A game theoretical model, *Health Economics* 27: 1821-42.

[6] Brekke, K., R. Cellini, L. Siciliani, O.R. Straume (2010), "Competition and quality in health care markets: a differential game approach", *Journal of Health Economics* 29: 508–523.

[7] Brekke, K.R., Cellini, R., Siciliani, L., Straume, O.R. (2012), "Competition in Regulated Markets with Sluggish Beliefs about Quality", *Journal of Economics & Management Strategy* 21: 131–178.

[8] Brekke, K.R., Siciliani, L., Straume, O.R. (2011), "Hospital Competition and Quality with Regulated Prices", *The Scandinavian Journal of Economics* 113: 444–469.

[9] Busse, R., Geissler, A., Quentin, W., Wiley, M. (2011), *Diagnosis-Related Groups in Europe: Moving towards transparency, efficiency and quality in hospitals*, London, Open University Press.

[10] Brekke, K.R. , Gravelle, H. , Siciliani, L. , Straume, O.R. (2014), Patient choice,mobility and competition among health care providers. In: Levaggi, R., Montefiori, M. (Eds.), *Health Care Provision and Patient Mobility, Developments in Health Economics and Public Policy*, Vol. 12. Springer-Verlag, Berlin, pp. 1–26 .

[11] Cashin, C., Chi, Y.L., Smith, P., Borowitz, M., Thomson, S. (2014), *Paying for Performance in Healthcare: Implications for Health System Performance and Accountability*, Open University Press.

[12] Cellini, R., Lambertini, L. (2004), "Dynamic oligopoly with sticky prices: closed-loop, feedback, and open-loop solutions", *Journal of Dynamical and Control Systems* 10: 303-314.

[13] Cellini, R., Siciliani, L., Straume, O.R. (2018), "A dynamic model of quality competition with endogenous prices", *Journal of Economic Dynamics and Control* 94: 190-206.

[14] Dockner, E.J., Jørgensen, S., Van Long, N., Sorger, G. (2000), *Differential Games in Economics and Management Science*, Cambridge, Cambridge University Press.

[15] Guccio, C., Lisi, D., Pignataro, G. (2016), "Readmission and Hospital Quality under Different Payment Regimes", *FinanzArchiv/Public Finance Analysis* 72: 453-474.

[16] Levaggi, R., Moretto, M., Pertile, P. (2012), "Static and dynamic efficiency of irreversible health care investments under alternative payment rules", *Journal of Health Economics* 31: 169-79.

[17] Lisi, D., Siciliani, L., Straume, O.R. (2018), "Hospital Competition under Pay-for-Performance: Quality, Mortality and Readmissions", *Discussion Papers 18/03*, Department of Economics, University of York.

[18] Longo, F., Siciliani, L., Moscelli, G., Gravelle, H. (2019), "Does hospital competition improve efficiency? The effect of the patient choice reform in England", *Health Economics*, forthcoming, doi: 10.1002/hec.3868.

[19] McAlister, F. A., Youngson, E., Kaul, P. (2017), "Patients with heart failure readmitted to the original hospital have better outcomes than those readmitted elsewhere", *Journal of the American Heart Association* 6: e004892.

[20] Milstein, R., Schreyoegg, J. (2016), "Pay for performance in the inpatient sector: A review of 34 P4P programs in 14 OECD countries", *Health Policy* 120(10): 1125-1140.

[21] Siciliani, L., Straume, O.R., Cellini, R. (2013), "Quality competition with motivated providers and sluggish demand", *Journal of Economic Dynamics and Control* 37: 2041–2061.

[22] Staples, J. A., Thiruchelvam, D., Redelmeier, D. A. (2014), "Site of hospital readmission and mortality: a population-based retrospective cohort study", *CMAJ open* 2(2): E77.

[23] Tsai, T.C., Orav, E.J., Jha, A.K. (2015), "Care fragmentation in the postdischarge period: surgical readmissions, distance of travel, and postoperative mortality", *JAMA surgery* 150(1): 59-64.

Appendix: The State-Feedback solution

In this Appendix we illustrate the underlying calculations for the state-feedback solution presented in Section 4. The hospital i's instantaneous profit is given by

$$pD - \frac{\theta}{2}q_i^2 - \frac{\beta}{2}D^2 - F + (\lambda p - r)\, D\,(1 - \delta q_i) \tag{A1}$$

which, together with the linear dynamic evolution of the state variable $\dot{D}(t) = \gamma\,(D^*(t) - D(t))$, gives rise to a linear-quadratic problem. In this class of problems, the solution can be found by guessing a quadratic form of the value function and, then, by finding the parameter values that meet the Bellman equation. Therefore, we assume that the value function of hospital i takes the following form:

$$V_i(D) = \alpha_0 + \alpha_1 D + \frac{\alpha_2}{2}D^2 \tag{A2}$$

which implies $\frac{\partial V_i}{\partial D} = \alpha_1 + \alpha_2 D$, and requires $\alpha_2 < 0$ in order to meet the concavity condition.

The Bellman equation associated with the hospital i's maximization problem is given by

$$\rho V_i(D) = \max\left\{pD - \frac{\theta}{2}q_i^2 - \frac{\beta}{2}D^2 - F + (\lambda p - r)\, D\,(1 - \delta q_i) + \frac{\partial V_i}{\partial D}\gamma\left(\frac{1}{2} + \frac{k\,(q_i - q_j)}{2\tau} - D\right)\right\}. \tag{A3}$$

Maximization yields $-\theta q_i - (\lambda p - r)\, D\delta + \frac{\partial V_i}{\partial D}\frac{\gamma k}{2\tau} = 0$, and after substituting $\frac{\partial V_i}{\partial D}$, we obtain

$$q_i = \phi_i(D) = \frac{\gamma k}{2\tau\theta}\left[\alpha_1 + \left(\alpha_2 - \frac{2\,(\lambda p - r)\,\delta\tau}{\gamma k}\right) D\right] \tag{A4}$$

and, by symmetry,

$$q_j = \phi_j(D) = \frac{\gamma k}{2\tau\theta}\left[\alpha_1 + \left(\alpha_2 - \frac{2\,(\lambda p - r)\,\delta\tau}{\gamma k}\right)(1 - D)\right]. \tag{A5}$$

Substituting (A4) and (A5) into (A3), yields

$$\begin{aligned}\rho V_i(D) \quad = \quad & pD - \frac{\theta}{2}\frac{\gamma^2 k^2}{4\tau^2\theta^2}\left[\alpha_1 + \left(\alpha_2 - \frac{2\,(\lambda p - r)\,\delta\tau}{\gamma k}\right) D\right]^2 - \frac{\beta}{2}D^2 - F \\ & + (\lambda p - r)\, D\left\{1 - \delta\frac{\gamma k}{2\tau\theta}\left[\alpha_1 + \left(\alpha_2 - \frac{2\,(\lambda p - r)\,\delta\tau}{\gamma k}\right) D\right]\right\} \\ & + (\alpha_1 + \alpha_2 D)\,\gamma\left[\frac{1}{2} + \frac{k}{2\tau}\left(\frac{\gamma k}{\tau\theta}\alpha_2 - \frac{2\,(\lambda p - r)\,\delta}{\theta}\right)\left(D - \frac{1}{2}\right) - D\right].\end{aligned} \tag{A6}$$

The value of parameters (i.e. $\alpha_0,\ \alpha_1,\ \alpha_2$) consistent with the above equality are given by the following system of equations:

$$\rho\alpha_0-\frac{\gamma}{2}\alpha_1+\frac{\gamma^2k^2}{8\theta\tau^2}\alpha_1^2+\frac{\gamma^2k^2}{4\theta\tau^2}\alpha_1\alpha_2-\frac{\gamma k}{2\theta\tau}\left(\lambda p-r\right)\delta\alpha_1+F=0 \tag{A7}$$

$$\left(\rho\alpha_1+\gamma\alpha_1-p-\left(\lambda p-r\right)-\frac{\gamma}{2}\alpha_2+\frac{\gamma^2k^2}{4\theta\tau^2}\alpha_2^2-\frac{\gamma^2k^2}{4\theta\tau^2}\alpha_1\alpha_2+\frac{\gamma k}{\theta\tau}\left(\lambda p-r\right)\delta\alpha_1-\frac{\gamma k}{2\theta\tau}\left(\lambda p-r\right)\delta\alpha_2\right)D=0 \tag{A8}$$

$$\left(\rho\frac{\alpha_2}{2}+\frac{\beta}{2}+\gamma\alpha_2-\frac{3\gamma^2k^2}{8\theta\tau^2}\alpha_2^2+\frac{\gamma k}{\theta\tau}\left(\lambda p-r\right)\delta\alpha_2-\frac{\left(\lambda p-r\right)^2\delta^2}{2\theta}\right)D^2=0 \tag{A9}$$

Condition (A9) provides two candidate solutions for α_2:

$$\alpha_2=\frac{2\theta\tau^2}{3\gamma^2k^2}\left[\left(2\gamma+\rho+\frac{\gamma k}{\theta\tau}2\left(\lambda p-r\right)\delta\right)\pm\sqrt{\left(2\gamma+\rho+\frac{\gamma k}{\theta\tau}2\left(\lambda p-r\right)\delta\right)^2+\frac{3\gamma^2k^2}{\theta^2\tau^2}\left(\theta\beta-\left(\lambda p-r\right)^2\delta^2\right)}\right] \tag{A10}$$

from which we take the negative root in order to ensure the concavity of the value function. Then, from (A8) we obtain:

$$\alpha_1=\frac{p+\left(\lambda p-r\right)+\frac{\gamma\alpha_2}{2}\left[1-\frac{\gamma k^2}{2\theta\tau^2}\left(\alpha_2-\frac{2(\lambda p-r)\delta\tau}{\gamma k}\right)\right]}{\gamma+\rho-\frac{\gamma^2k^2}{4\theta\tau^2}\left(\alpha_2-\frac{4(\lambda p-r)\delta\tau}{\gamma k}\right)}. \tag{A11}$$

Following the same argument as in Brekke et al. (2012, p. 170), it can be shown that α_1 is positive for all permissible parameter configurations. Finally, α_0 can be easily obtained by substituting (A10) and (A11) into (A7).