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Investment and Quality Competition in Healthcare Markets *

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Abstract

We study the strategic relationship between hospital investment in health technologies and provision of service quality. We use a spatial competition framework with altruistic providers and allow for hospital investment and quality provision to be either complements or substitutes in the patient health benefit and provider cost functions. We assume that each hospital commits to a certain investment level before deciding on the provision of service quality. We show that, compared to a simultaneous-move benchmark, providers' lack of ability to commit to a particular quality level generally leads to either under- or overinvestment. Underinvestment arises when the price-cost margin is positive and when quality and investments are strategic complements. In turn, this has implications for the optimal design of hospital payment contracts. We show that, differently from the simultaneous-move case, the first-best solution is generally not attainable by setting the fixed price at the appropriate level, but the regulator must complement the payment contract with at least one more instrument to address under- or overinvestment. We also analyse the welfare effects of different policy options (separate payment for investment, through a higher per-treatment price, or refinement of pricing) to reimburse hospitals for their investments.

Keywords: Investment; Quality competition; Hospital payment.

JEL Classification: D24, I11, I18, L13

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1 Introduction

Investments in medical innovations and new technologies can improve the efficacy of treatments and enhance patient outcomes (Fuchs and Sox, 2001; Cutler and McClellan, 2001), and in some cases reduce the cost of providing medical care. For example, laparoscopic surgery can both improve health outcomes and reduce length of stay and treatment costs, leading to substantial efficiency gains in service provision, therefore freeing up resources to improve care for other patients. But costly investments can also put pressure on the sustainability of health spending in publicly-funded health systems (Smith et al., 2009; OECD, 2010). In 2018, EU member states allocated around 0.4 percent of their GDP on capital investment in the health sector. Similarly, the European Structural and Investment Funds provided more than EUR 9 billion to member states for health-related investments in 2014-2020 (OECD, 2020).

Hospital spending accounts for a significant share of health spending, about 39% in 2018 across the EU. The dominant payment model for hospitals across the OECD is activity-based funding, where hospitals are reimbursed a fixed price based on a Diagnosis Related Group (DRG) for each patient treated. Hospitals compete on quality to attract patients with higher quality leading to higher demand and higher revenues. There is instead more variety in the arrangements used to reimburse hospitals for their investments. These can take the form of separate supplementary payments, either as additional funding or retrospective reimbursement (Scheller-Kreinsen et al., 2011). Alternatively, the investment cost can be covered and included in the DRG fixed price, or it can be taken into account when designing DRG groups, for example by splitting an existing DRG or by establishing a new DRG, especially when the new technologies increase costs for a well-defined subset of patients (Quentin et al., 2011; HOPE, 2006).

Despite the importance of hospital investments, there is limited understanding of how hospitals make investment decisions, and in turn how these decisions affect the provision of care. This study develops a theoretical model to investigate how hospitals' investment decisions are affected by different payment arrangements. We do so in a general environment where hospitals also compete for patients based on the quality of care they provide, which allows us to explore the interaction between investment and service quality. We address several questions. What determines hospitals' incentives to invest in new medical technology, and do these incentives lead to underinvestment or overinvestment? Similarly, do hospitals' investment incentives lead to under- or overprovision of quality of care? What is the optimal payment contract and what are the welfare implications of different policies regarding payment for medical innovations?

In order to answer these questions, we use a spatial competition framework where hospitals are partly altruistic and we allow for investment and service quality to be either substitutes or complements in the health benefit and cost functions. We also assume that hospitals are financed by a third-party payer with a per-treatment price and a lump-sum transfer, where each of the policy instruments might depend on the level of investment. As a benchmark, we derive the equilibrium levels of investment and service quality under the assumption that these decisions are made simultaneously. We then proceed by considering the arguably more realistic setting of a two-stage game, where each hospital commits to a certain investment level before deciding on the provision of service quality. A key question addressed in this part of our analysis is whether sequential decision making leads to over- or underinvestment, and we find that the answer to this question depends crucially on two different factors: (i) whether the treatment price is higher or lower than the marginal treatment cost in equilibrium, which in turn depends on the degree of provider altruism, and (ii) whether increased investment by one hospital will spur an increase or a reduction in the quality provision of the competing hospital. If the price-cost margin is *positive*, we show that hospitals underinvest (overinvest) if own investment and the quality of the competing hospital are strategic complements (substitutes). On the other hand, if the price-cost margin is *negative*, strategic substitutability leads to underinvestment whereas strategic complementarity leads to overinvestment. Whether own investment and rival's quality are strategic substitutes or complements depends in turn on the characteristics of the hospital cost and patient benefit functions.

In the second part of the paper we offer a welfare analysis. A key underlying assumption is that, although service quality is observable, it is not verifiable and thus not contractible (Laffont and Martimort, 2009). Investments, on the other hand, are both observable and verifiable. Thus, regulators can design payment contracts based on investment with the purpose of indirectly incentivising quality improvements, which is one of the key objectives of hospital regulation. We start out by deriving the *first-best solution* and show that it can be implemented by a simple payment contract, consisting only of a fixed DRG tariff, as long as investment and quality choices are made simultaneously. However, if these decisions are made sequentially, the first-best solution is generally not attainable, since the price that induces the first-best quality level will lead to either under- or overinvestment. In this case, the regulator must complement the payment contract with at least one more instrument to correctly incentivise investments, either through a lump-sum payment or a treatment price which depends on investment. We show that the regulator has to incentivise investment when (i) investment and quality are strategic complements and the provider works at a positive price cost-margin, or (ii) investment and quality are strategic substitutes and the provider works at a negative price cost margin.

Finally, under the realistic assumption that payment contracts do not generally coincide with the ones that implement the first-best solution, we study the welfare effects of several plausible policies and payment mechanisms. First, we show that the introduction of a separate payment which directly incentivises investment can be welfare improving if, for example, investment and quality are initially below the first-best levels and investment and quality are complements or if they are substitutes but the degree of substitutability is sufficiently small. Second, we find that paying for investments through a higher activity-based tariff per patient treated, rather than through a separate funding scheme, can also be welfare improving if equilibrium investment and quality are below the first-best level and a higher DRG tariff increases the marginal revenue of both investment and service quality. Finally, we find that a policy incentivising investment through refinements of DRG pricing (so that additional investments are rewarded with a higher per unit price) stimulates quality provision while the effect on investment is, perhaps surprisingly, *a priori* ambiguous. Since such a payment scheme reinforces each hospital's incentive to use own investments to strategically affect the rival's quality provision, this could lead to a counterproductive outcome (i.e., lower investments) if own investment and rival's quality are strategic complements and providers are sufficiently profit oriented.

The rest of the paper is organised as follows. In the next section, we discuss the existing literature. In Section 3, we describe the key assumptions of the model. In Section 4, we derive the benchmark scenario where decisions on investments and service quality are made simultaneously. In Section 5, we consider the more realistic scenario of sequential decision making where hospitals first decide on investment and then on service quality. Section 6 is devoted to a welfare analysis where we adopt both a normative approach, to derive the socially optimal level of investment and quality and optimal regulation, and a more positive approach by investigating possible policy reforms to incentivise hospital investments. Section 7 concludes and discusses policy implications.

2 Related Literature

Our study contributes and integrates two strands of the literature. The first one is the literature on quality competition in regulated markets, using a spatial framework, where key contributions include Wolinsky (1997), Gravelle (1999), Beitia (2003), Karlsson (2007) and Brekke et al. (2007, 2011), among many others. This literature identifies the conditions under which competition amongst providers increases or reduces quality provision under different assumptions on providers' objective function, including altruistic preferences, non-profit status and costs. Using a similar spatial framework, but assuming an unregulated market, Brekke et al. (2010) investigate price and quality competition in a simultaneous-move game. They find that equilibrium quality is always below the socially optimal level when the utility function of consumers is concave in consumption, therefore allowing for the presence of income effects. Incentives for underprovision are reinforced if instead quality choices are made before price competition takes place, which gives the firms an incentive to reduce quality provision in order to dampen price competition, as first shown by Ma and Burgess (1993). Finally, Brekke et al. (2006) analyse optimal regulation in a sequential-game framework with location and quality choices and find that the optimal price induces first-best quality, but horizontal differentiation is inefficiently large if the regulator cannot commit to a price before the location choices. None of these studies makes a distinction between investments and service quality.[1]

The second strand of literature investigates investment decisions and implications for regulation and design of optimal payment systems. One key issue addressed in this literature is the timing of investment and how this might be affected by different regulatory schemes. For example, using a real options approach, Levaggi and Moretto (2008) find that long-term contracts are more effective in offering incentives for a provider to invest early. This analysis is extended by Pertile (2008) to account for cost uncertainty, investigating the optimal timing of investment in new healthcare technologies by providers competing for patients. The analysis reveals a potentially counterintuitive relationship between payment characteristics and investment decisions, for example that a more generous payment scheme does not necessarily lead to earlier investment. In another related study, Levaggi et al. (2012) address how uncertainty about patients' benefits affects the incentives to

[1] There is also a recent literature on multi-stage competition, including quality choices, in mixed oligopolies. For example, Laine and Ma (2017) use a model of vertical differentiation, where firms first choose product qualities, then simultaneously choose prices. Ghandour (forthcoming) investigates quality competition under asymmetric pricing in a sequential game. Hehenkamp and Kaarbøe (2020) explore location choices and quality competition in mixed hospital markets. However, a distinction between investments and service quality is not made in any of these papers.

invest in new technologies. They find that efficiency can be ensured both in the time of adoption (dynamic efficiency) and the intensity of use of technology (static efficiency) if reimbursement by the purchaser includes both a variable (per-patient) component and a lump-sum component.[2] A similar conclusion is reached by Levaggi et al. (2014), who show that it is optimal to pay the provider based on a fixed fee per patient and a lump-sum component to fund capital costs separately, a result which loosely resembles some of the insights derived in our welfare analysis.

Another key issue, with important regulatory implications, is contractibility. Whereas we in the present paper assume that investment is a contractible variable while service quality is not, Bös and De Fraja (2002) consider only non-contractible investments (interpreted as 'quality'). Using an incomplete contract framework, they focus on the effects of investment by the health care authority in contingency plans, which give it the option to purchase care from outside providers. In the first stage, hospitals choose investment decisions before patients are treated in the second stage. In such a setting, hospitals underinvest in quality while the health authority overinvests in the contingency arrangements, as compared to the first-best outcome.

A common feature of all the above mentioned papers is that quality is a one-dimensional variable which may or may not be modelled as an investment decision, and which may or may not be contractible. In contrast, we make a conceptual separation between investment in medical technologies and other dimensions of quality provision, which we subsume under the umbrella term 'service quality', assuming that the former is contractible whereas the latter is not. We argue that this is a meaningful and potentially important conceptual distinction, and the main contribution of our paper is to study the interaction between investment and quality in healthcare markets.

3 Model

Consider a market for a healthcare treatment offered by two hospitals, denoted by $i = \{1, 2\}$, located at opposite endpoints of a Hotelling line of length 1. Patients are uniformly distributed on the unit line with a mass of one. Each patient demands one unit of treatment from the most preferred provider. A patient located at x who is treated at Hospital i has the utility

$$U_i(x, I_i, q_i) = B(I_i, q_i) - t\,|x - z_i|\,, \tag{1}$$

[2] In a non-competitive setting with demand uncertainty, Barros and Martinez-Giralt (2015) also study the relationship between payment systems and the rate of technology adoption. They find that a mixed cost reimbursement system can induce a higher adoption of health technologies compared to the DRG payment system.

where $B(I_i, q_i)$ is patient health benefit from treatment, q_i is service quality of treatment at Hospital i, I_i is investment in new technologies, t is the transportation cost per unit of distance, and z_i is hospital location with $z_1 = 0$ and $z_2 = 1$. We assume that the patient health benefit is given by

$$B(I_i, q_i) = b^I I_i + b^q q_i + b^{Iq} I_i q_i, \tag{2}$$

where $b^q > 0$, $b^I \geq 0$ and $b^{Iq} \gtrless 0$, and where the relevant values of q_i and I_i are such that $b^q + b^{Iq} I_i > 0$ and $b^I + b^{Iq} q_i \geq 0$, implying that patient health benefit is increasing in service quality and (weakly) increasing in investment. We allow service quality and investment to be either complements ($b^{Iq} > 0$) or substitutes ($b^{Iq} < 0$) in health benefits, so that investments can amplify or dampen the effect of service quality on health benefits.

One example of investment is Magnetic Resonance Imaging (MRI) machines (Baker, 2001), which are used to facilitate the diagnosis of a condition or improve its assessment. Such investment can have both a direct effect on patient health ($b^I > 0$), for example the scan reveals a tumor, and an indirect effect by allowing to tailor the provision of care to the specific needs of the patients revealed by the scan, therefore increasing the effectiveness of quality provision ($b^{Iq} > 0$). Another example is investment in less invasive laparoscopic (endoscopic) technologies used for surgical interventions (e.g., for removal of gallbladder). The less invasive approach improves health outcomes through quicker recovery time, less pain, lower risks of complications, infections and transfusions, relative to more invasive open surgeries. Laparoscopy can also facilitate diagnosis therefore increasing the effectiveness of quality provision. There is also increasing interest in investment in robotic minimally invasive surgery which potentially increases precision, and reduces scope for errors.

Suppose that each patient in the market makes a utility-maximising choice of hospital and that patient health benefit is sufficiently high to ensure full market coverage. The demand function for Hospital i is then given by

$$D_i(I_i, I_j, q_i, q_j) = \frac{1}{2} + \frac{B(I_i, q_i) - B(I_j, q_j)}{2t}, \tag{3}$$

with demand for the rival hospital given by $D_j(I_i, I_j, q_i, q_j) = 1 - D_i(I_i, I_j, q_i, q_j)$.

The hospital cost function is assumed to be given by

$$C(D_i, I_i, q_i) = c(I_i, q_i) D_i + k(I_i), \tag{4}$$

where $c(I_i, q_i)$ is the cost per patient treated, which we refer to as marginal treatment costs, and $k(I_i)$ is the fixed cost of investment (e.g., a new MRI machine), which is increasing in investment and convex, $\partial k(I_i)/\partial I_i > 0$ and $\partial^2 k(I_i)/\partial I_i^2 > 0$. We assume that marginal treatment costs are given by

$$c(I_i, q_i) = c^I I_i + c^q q_i^2 + c^{Iq} I_i q_i, \tag{5}$$

where $c^q > 0$, $c^I \gtrless 0$ and $c^{Iq} \gtrless 0$. We assume that marginal treatment costs of service quality are positive, $2c^q q_i + c^{Iq} I_i > 0$, and treatment costs are convex in quality. We allow for service quality and investment to be either cost complements ($c^{Iq} < 0$) or substitutes ($c^{Iq} > 0$). We also allow the marginal treatment costs to increase or decrease with higher investment ($c^I \gtrless 0$). For example, laparoscopic surgery generally reduces the length of stay in hospital, in many cases allowing same-day discharge, requires fewer medications and only local anesthesia (as opposed to general anesthesia), therefore reducing the cost of quality provision during hospitalisation. Instead, investments in robot-assisted surgery as for robotic radical prostatectomy for treatment of localised prostate cancer can increase treatment costs relative to surgery by hand due to the specialised nature of the equipment (Ramsay et al., 2012; Park et al., 2012). Similarly, investing in MRI machines is expensive and the MRI scans cost more that CT scans. Therefore, whether investments increase or decrease treatment costs varies across technologies. Whether quality and investments are complements or substitutes is also in principle indeterminate. Laparoscopy or robotic surgery requires more doctor training, and can also take longer time than open surgery (especially if preparation time is included). A better diagnosis through an MRI scan can allow doctors to choose a treatment which is better suited for patients' needs therefore reducing unnecessary care, and reducing the cost of quality provision.

We assume that hospitals are prospectively financed by a third-party payer with a per-treatment price $p(I_i)$ and a fixed budget component or lump-sum transfer equal to $T(I_i)$. The fixed budget component ensures providers' participation in the market. Moreover, most countries use some form of payment that entails additional funding to hospitals to cover certain investments in technologies, including retrospective reimbursement of hospital reported costs outside the DRG price system (Sorenson et al., 2015). We therefore assume that the fixed budget component can be either independent of investment, $\partial T(I_i)/\partial I_i = 0$, or increasing in investment, $\partial T/\partial I_i > 0$, where part or all of the cost of new investments are reimbursed by the funder.

If the price is fixed (as in most DRG payment schemes) then $\partial p/\partial I_i = 0$. Although the price is fixed in this scenario, the price level can still vary depending on whether the payment system is designed to cover the investment costs. Some countries pay a higher fixed price which is meant to include investments costs, while others pay a lower price which is meant to cover treatment costs only (Scheller-Kreinsen et al., 2011). We also allow for the possibility that the price is increasing in investment, $\partial p(I_i)/\partial I_i > 0$. This assumption is consistent with payment mechanisms that allow DRGs to be split when a new technology becomes available (Quentin et al., 2011; HOPE, 2006).

Lastly, we assume that the regulator is able to pre-commit to a particular reimbursement policy for investments in health technologies. The hospital payment scheme described above relies on the assumption that investment in medical machinery and technology is verifiable, and thus contractible, while the hospitals' provision of service quality is not.[3] This assumption implies that hospital payments can be made contingent on investment. The hospitals' provision of quality, on the other hand, can only be indirectly incentivised, either through the per-treatment price, p, which affects the hospitals' incentives to attract demand, or through the payment for investment, $T(I_i)$, which affects the marginal benefits and costs of quality provision via changes in the hospitals' investment decisions (if $b^{Iq} \neq 0$ and $c^{Iq} \neq 0$).

The financial surplus of Hospital i, denoted π_i, is given by

$$\pi_i(I_i, I_j, q_i, q_j) = T(I_i) + [p(I_i) - c(I_i, q_i)]\, D_i(I_i, I_j, q_i, q_j) - k(I_i). \tag{6}$$

In line with the existing literature (e.g., Ellis and McGuire, 1986; Chalkley and Malcomson, 1998) we assume that hospitals are partly altruistic and care about the health benefit of the average patient. The objective function of Hospital i, denoted by V_i, is thus given by

$$V_i(I_i, I_j, q_i, q_j) = \alpha B(I_i, q_i) + \pi_i(I_i, I_j, q_i, q_j), \tag{7}$$

where α is a positive parameter measuring the degree of provider altruism.

4 Simultaneous choices of investment and quality

As a benchmark for comparison, suppose that both hospitals choose investment in technology and service quality simultaneously. The Nash equilibrium is implicitly characterised by the first-order

[3] More precisely, we assume that quality is observable but not verifiable, and thus not contractible.

conditions for hospital choice of q_i and I_i given by

$$\frac{\partial V_i(I_i,I_j,q_i,q_j)}{\partial q_i} = \left(b^q + b^{Iq} I_i\right)\left[\alpha + \frac{p(I_i) - c(I_i,q_i)}{2t}\right] - \left(2c^q q_i + c^{Iq} I_i\right) D_i(I_i,I_j,q_i,q_j) = 0, \quad (8)$$

$$\begin{aligned}\frac{\partial V_i(I_i,I_j,q_i,q_j)}{\partial I_i} &= \left(b^I + b^{Iq} q_i\right)\left[\alpha + \frac{p(I_i) - c(I_i,q_i)}{2t}\right] + \frac{\partial T(I_i)}{\partial I_i} \\ &+ \left[\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right] D_i(I_i,I_j,q_i,q_j) - \frac{\partial k(I_i)}{\partial I_i} = 0 \,. \quad (9)\end{aligned}$$

The second-order conditions are provided in the Appendix A1. The optimal level of service quality is set such that the marginal benefit from the altruistic health gain and the marginal revenue is traded-off against the higher costs from higher demand and higher per-patient treatment costs. The optimal level of investment is analogous. The marginal benefit from investment includes the altruistic health gain and the marginal revenues from higher demand, and potentially also a higher price and higher lump-sum transfer. Investment is optimally provided when the sum of marginal benefit is equal to marginal treatment costs from higher demand and the marginal investment cost (higher fixed costs), given by the final term in (9). Investment also affects per-patient cost, which will contribute to the marginal benefit of investments if cost reducing, $c^I + c^{Iq} q_i < 0$, or the marginal cost if cost augmenting, $c^I + c^{Iq} q_i > 0$.

At the symmetric equilibrium both hospitals choose quality and investment (denoted by q^* and I^*) which are implicitly given by[4]

$$V_q(I^*,q^*) = \left(\alpha + \frac{p(I^*) - c(I^*,q^*)}{2t}\right)\left(b^q + b^{Iq} I^*\right) - \frac{\left(2c^q q^* + c^{Iq} I^*\right)}{2} = 0, \quad (10)$$

$$\begin{aligned}V_I(I^*,q^*) &= \left(\alpha + \frac{p(I^*) - c(I^*,q^*)}{2t}\right)\left(b^I + b^{Iq} q^*\right) + \frac{\partial T(I^*)}{\partial I} \\ &+ \frac{1}{2}\left(\frac{\partial p(I^*)}{\partial I} - \left(c^I + c^{Iq} q^*\right)\right) - \frac{\partial k(I^*)}{\partial I} = 0 \,. \quad (11)\end{aligned}$$

We use these expressions to compare the equilibrium under sequential choices, derived in the next section.

[4] An interior solution with a positive level of service quality requires that the per-unit price p is sufficiently high.

5 Sequential choices of investment and quality

In this section, we make the arguably more realistic assumption that hospitals make their investment decisions before the treatment quality decisions. This modelling approach is plausible given that investment decisions take time and are infrequent and hospitals invest before starting to treat patients, which is when service quality is provided. We therefore consider the following two-stage game:

Stage 1 Both providers choose simultaneously how much to invest.

Stage 2 Both providers simultaneously choose their service quality.

As usual, the game is solved by backward induction.

5.1 Quality competition

For a given pair of investment levels (I_i, I_j), the level of service quality that maximises the payoff of Hospital i is implicitly given by (8), and an analogous condition holds for Hospital j. In order to determine how the investment made by Hospital i affects the quality chosen by the two hospitals, we totally differentiate the system of first-order conditions given by $\partial V_i(I_i, I_j, q_i, q_j)/\partial q_i = 0$ and $\partial V_j(I_i, I_j, q_i, q_j)/\partial q_j = 0$ with respect to I_i by applying Cramer's Rule (see Appendix A2.1), yielding

$$\frac{\partial q_i(I_i, I_j)}{\partial I_i} = \frac{1}{\Delta}\left(\begin{array}{c} -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j\right) \\ +\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ +\left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \end{array}\right) \tag{12}$$

and

$$\frac{\partial q_j(I_i, I_j)}{\partial I_i} = \frac{1}{\Delta}\left(\begin{array}{c} \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t}\left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{2t} + c^q D_i\right) \\ +\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t}\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ +\left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \end{array}\right), \tag{13}$$

where $\Delta > 0$ is given by (A16) in Appendix A2.1. The sign of (12) determines whether investment and quality for Hospital i are substitutes ($\partial q_i/\partial I_i < 0$) or complements ($\partial q_i/\partial I_i > 0$). The sign of

(13) determines whether the investment of Hospital i's and the quality of Hospital j are strategic substitutes ($\partial q_j/\partial I_i < 0$) or strategic complements ($\partial q_j/\partial I_i > 0$). Both of these expressions have an *a priori* indeterminate sign.

As a benchmark, consider the case in which I_i and q_i are neither complements nor substitutes in costs ($c^{Iq} = 0$) and benefits ($b^{Iq} = 0$), and where any increase in the marginal cost of investments is exactly offset by a marginal increase in price so that the price-cost margin remains unchanged ($\partial p(I_i)/\partial I_i - c^I = 0$). In this case (12)-(13), reduce to

$$\frac{\partial q_i}{\partial I_i} = -\frac{q_i b^I \left(q_j b^q + 2tD_j\right)}{3\left(b^q\right)^2 q_j q_i + 4t\left(D_j q_i b^q + D_i q_j b^q + tD_i D_j\right)} < 0 \tag{14}$$

and

$$\frac{\partial q_j}{\partial I_i} = \frac{q_j b^I \left(q_i b^q + tD_i\right)}{3\left(b^q\right)^2 q_j q_i + 4t\left(D_j q_i b^q + D_i q_j b^q + tD_i D_j\right)} > 0. \tag{15}$$

Thus, own investment and own quality are substitute strategies (i.e., $\partial q_i/\partial I_i < 0$) whereas own investment and rival's quality are strategic complements (i.e., $\partial q_j/\partial I_i > 0$). The intuition for this is fairly straightforward. All else equal, higher investment by Hospital i shifts demand from Hospital j to Hospital i (as long as $b^I > 0$). Because marginal treatment costs are increasing in quality, such a demand shift leads to higher (lower) marginal cost of quality provision for Hospital i (Hospital j), as can be seen from the third term in (8). Consequently, a higher investment by Hospital i leads to lower (higher) service quality by Hospital i (Hospital j), all else equal.

The effects in this benchmark scenario can be either reinforced or weakened by the presence of *three additional effects*. First, if higher investment increases (reduces) the price-cost margin of Hospital i, this will increase (reduce) the profitability of attracting more demand by offering higher service quality, thus leading to higher (lower) quality offered by Hospital i, all else equal. Second, if investment and quality are complements (substitutes) in the benefit function (i.e., if $b^{Iq} > (<) \, 0$), this will increase (reduce) both the demand responsiveness and the marginal health benefit gain of quality provision, thus leading to higher (lower) quality offered by Hospital i, all else equal. Third, if investment and quality are complements (substitutes) in the cost function (i.e., if $c^{Iq} < (>) \, 0$), this will reduce (increase) the marginal cost of quality provision, thus leading to higher (lower) quality chosen by Hospital i, all else equal.

Each of these three additional effects work in the same direction for both $\partial q_i/\partial I_i$ and $\partial q_j/\partial I_i$. In other words, an effect that establishes a *ceteris paribus* positive effect of I_i on q_i also implies a *ceteris paribus* positive effect of I_i on q_j. The reason is that qualities are strategic complements in the second-stage subgame, as defined by $\partial^2 V_i/\partial q_i \partial q_j = \left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_j\right)/2t > 0$ (see Appendix A2.1). This strategic relationship is due to the assumption that the marginal cost of quality provision increases with demand ($\partial^2 C/\partial D_i \partial q_i = 2c^q q_i + c^{Iq} I_i > 0$). All else equal, higher quality provision by Hospital i leads to lower demand for Hospital j, which reduces the marginal cost of quality provision and thus increases the optimal quality choice for the latter hospital.

Finally, note that it is possible for own investment and quality to be complements, $\partial q_i/\partial I_i > 0$. This arises for example if investment has no effect on health benefits, but reduces costs, and benefit and cost are independent ($b^{Iq} = c^{Iq} = b^I = 0$ and $c^I < 0$), so that

$$\frac{\partial q_i\left(I_i, I_j\right)}{\partial I_i} = \frac{c^q b^q}{t\Delta}\left(\frac{q_j b^q}{t} + D_j\right)\left(\frac{\partial p(I_i)}{\partial I_i} - c^I\right) > 0 \tag{16}$$

and

$$\frac{\partial q_j\left(I_i, I_j\right)}{\partial I_i} = \frac{c^q \left(b^q\right)^2 q_j}{2t^2\Delta}\left(\frac{\partial p(I_i)}{\partial I_i} - c^I\right) > 0. \tag{17}$$

5.2 Investment decisions

In the first stage of the game, hospitals decide how much to invest, taking into account the effect that the investment will have on quality decisions of both hospitals in the second stage. The first-order condition for Hospital i is given by

$$\begin{aligned}\frac{\partial V_i(I_i, I_j, q_i, q_j)}{\partial I_i} = {} & \left(b^I + b^{Iq} q_i\right)\left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right) D_i \\ & + \frac{\partial T(I_i)}{\partial I_i} - \frac{\partial k(I_i)}{\partial I_i} - \frac{b^q + b^{Iq} I_j}{2t}\left[p(I_i) - c(I_i, q_i)\right]\frac{dq_j}{dI_i} \\ & + \left[\left(b^q + b^{Iq} I_i\right)\left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] - \left(2c^q q_i + c^{Iq} I_i\right) D_i\right]\frac{dq_i}{dI_i} = 0.\end{aligned} \tag{18}$$

The second order condition is provided in Appendix A2.2. The first line and the first two terms in the second line in (18) are identical to the investment condition in the simultaneous-move version of the game given by (9). The two additional terms in the second and third line of (18) capture the strategic effects of Hospital i's investment on the quality choices of both hospitals. However, the third line in (18) is equal to zero due to the envelope theorem; given that Hospital i chooses a payoff-maximising quality level, the expression in the square bracket is zero (see (8)).

Applying symmetry, quality and investment in the symmetric subgame-perfect Nash equilibrium (denoted by q^{**} and I^{**}) are implicitly given by

$$V_q(I^{**},q^{**}) = \left(\alpha + \frac{p(I^{**}) - c(I^{**},q^{**})}{2t}\right)\left(b^q + b^{Iq}I^{**}\right) - \frac{2c^q q^{**} + c^{Iq}I^{**}}{2} = 0, \tag{19}$$

and

$$\begin{aligned} V_I(I^{**},q^{**}) &= \left(\alpha + \frac{p(I^{**}) - c(I^{**},q^{**})}{2t}\right)\left(b^I + b^{Iq}q^{**}\right) + \frac{\partial T(I^{**})}{\partial I} \\ &+\frac{1}{2}\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right) - \frac{\partial k(I^{**})}{\partial I} \\ &-\frac{\left(b^q + b^{Iq}I^{**}\right)}{2t}\left[p(I^{**}) - c(I^{**},q^{**})\right]\frac{\partial q_j\left(I^{**}\right)}{\partial I_i} = 0 \end{aligned} \tag{20}$$

where

$$\frac{\partial q_j\left(I^{**}\right)}{\partial I_i} = \frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)}{4t\Delta}\left(\begin{array}{c} c^q\left(b^I + b^{Iq}q^{**}\right) \\ +\left(b^q + b^{Iq}I^{**}\right)\left(\begin{array}{c} b^{Iq}\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{\left(b^q+b^{Iq}I^{**}\right)} - c^{Iq} \\ +\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)\left(b^I+b^{Iq}q^{**}\right)}{t} \\ +\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right)\frac{b^q+b^{Iq}I^{**}}{t}\end{array}\right)\end{array}\right). \tag{21}$$

Comparing (10) and (19), we see that equilibrium quality is identical under the simultaneous and sequential solution if and only if $I^* = I^{**}$. On the other hand, equilibrium investment is generally different when $q^* = q^{**}$. Comparing (11) and (20), the difference in the investment conditions is given by the last term in (20), which captures the strategic effect of own investment on the competing hospital's quality choice in the second stage. It follows that equilibrium investment and quality are the same under simultaneous and sequential decision making (i.e., $q^* = q^{**}$ and $I^* = I^{**}$) only if the investment of Hospital i has no strategic effect on the quality choice of Hospital j (i.e., if $\partial q_j\left(I^{**}\right)/\partial I_i = 0$).

Whether hospitals have an incentive to over- or underinvest in medical technology depends on the sign of $\partial q_j\left(I^{**}\right)/\partial I_i$ and the price-cost margin, $p(I^{**}) - c(I^{**},q^{**})$, which can be positive or negative depending on the degree of altruism.[5] Suppose that the price cost margin is

[5] To see that this is the case, we can re-write

$$V_q(I^{**},q^{**}) = 0$$

as

$$p(I^{**}) - c(I^{**},q^{**}) = 2t\left(\frac{2c^q q^{**} + c^{Iq}I^{**}}{2\left(b^q + b^{Iq}I^{**}\right)} - \alpha\right).$$

positive in equilibrium. There is *underinvestment* if own investment and rival's quality choice are *strategic complements* ($\partial q_j(I^{**})/\partial I_i > 0$) and *overinvestment* if they are *strategic substitutes* ($\partial q_j(I^{**})/\partial I_i < 0$). The intuition is related to the strategic complementarity of quality choices in the second-stage subgame (i.e., $\partial^2 V_i/\partial q_i \partial q_j > 0$). If $\partial q_j/\partial I_i > 0$, each hospital has a strategic incentive to reduce investment at the first stage of the game in order to dampen quality competition at the second stage. These incentives are reversed if $\partial q_j/\partial I_i < 0$, which implies that quality competition can be dampened by *increasing* investment. The results are however reversed if the price-cost margin is negative, which requires a sufficiently high degree of altruism.

We summarise this first result in the following proposition:

Proposition 1 *Hospitals underinvest in a sequential game, relative to a simultaneous game, if (i) the price-cost margin is positive,* $p(I^{**}) - c(I^{**}, q^{**}) > 0$, *and investments and rival's quality are strategic complements,* $\partial q_j(I^{**})/\partial I_i > 0$, *or if (ii) the price-cost margin is negative,* $p(I^{**}) - c(I^{**}, q^{**}) < 0$, *and investments and rival's quality are strategic substitutes,* $\partial q_j(I^{**})/\partial I_i < 0$. *Hospitals overinvest if (i) the price-cost margin is positive,* $p(I^{**}) - c(I^{**}, q^{**}) > 0$, *and investments and rival's quality are strategic substitutes,* $\partial q_j(I^{**})/\partial I_i < 0$, *or if (ii) the price-cost margin is negative,* $p(I^{**}) - c(I^{**}, q^{**}) < 0$, *and investments and rival's quality are strategic complements,* $\partial q_j(I^{**})/\partial I_i > 0$.

We now turn to the comparison of quality. Whether the hospitals over- or under-provide quality relative to the simultaneous game, depends on whether investment and quality are complements or substitutes in equilibrium, which from (19) depends on the sign of

$$\frac{\partial V_q(I^{**}, q^{**})}{\partial I} = \frac{\left(b^q + b^{Iq} I^{**}\right)}{2t} \left[\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right)\right] + b^{Iq} \left(\frac{2c^q q^{**} + c^{Iq} I^{**}}{2\left(b^q + b^{Iq} I^{**}\right)}\right) - \frac{c^{Iq}}{2}. \tag{22}$$

If the price-cost margin increases with investment, $\partial p(I^{**})/\partial I - \left(c^I + c^{Iq} q^{**}\right) > 0$, quality and investment are always complements if they are complements in health benefits and costs, but the scope for complementarity instead reduces if investment and quality are substitutes in health benefits and costs.

We summarise our second result in the following proposition:

Proposition 2 *Quality is underprovided in a sequential game, relative to a simultaneous game, if* *(i) hospitals underinvest, and investment and quality are complements, $\partial V_q(I^{**}, q^{**})/\partial I > 0$, or if (ii) hospitals overinvest, and investment and quality are substitutes, $\partial V_q(I^{**}, q^{**})/\partial I < 0$. Instead, quality is overprovided if (i) hospitals underinvest, and investment and quality are substitutes, $\partial V_q(I^{**}, q^{**})/\partial I < 0$, or if (ii) hospitals overinvest, and investment and quality are complements, $\partial V_q(I^{**}, q^{**})/\partial I > 0$.*

To gain some further insights on whether sequential decision making leads to higher or lower investments, and higher or lower quality provision, we will consider a few special cases which allow us to isolate each of the different mechanisms at play and link them to the basic assumptions of our model. In each case, the results depend on whether each hospital's price-cost margin is positive or negative in equilibrium, which in turn depends on the degree of altruism. More specifically, the price-cost margin is positive if the hospitals are sufficiently profit-oriented, and negative if they are sufficiently altruistic:

$$p(I^{**}) - c(I^{**}, q^{**}) > (<)\, 0 \quad if \quad \alpha < (>)\, \widehat{\alpha} := \frac{2c^q q^{**} + c^{Iq} I^{**}}{2\left(b^q + b^{Iq} I^{**}\right)}. \tag{23}$$

We present the different cases as four separate Lemmas, starting with what we have previously referred to as a benchmark case.

Lemma 1 *Suppose that investment and quality are cost and benefit independent ($c^{Iq} = b^{Iq} = 0$), and that investments have no effect on the price-cost margin ($\partial p(I^{**})/\partial I - c^I = 0$). In this case, quality provision is identical under sequential and simultaneous choices, whereas hospitals underinvest in the sequential game if $\alpha < \widehat{\alpha}$ and overinvest if $\alpha > \widehat{\alpha}$.*

In the benchmark case, where investment and quality are independent in the health benefit and costs functions, and where investments do not affect the price-cost margin, the equilibrium level of investments have no effect on each hospital's incentive for quality provision, i.e., $\partial V_q(I^{**}, q^{**})/\partial I = 0$, which implies that equilibrium quality provision is the same in the two versions of the game. Investment incentives, on the other hand, are affected through the term $\partial q_j\left(I^{**}\right)/\partial I_i$, which is unambiguously positive in the benchmark case. All else equal, higher investment by one hospital leads to higher quality provision by the competing hospital, because of lower marginal cost of quality provision caused by lower demand. This creates a strategic incentive in the sequential game that affects the optimal investment decision. As long as the price-cost margin is positive, each hospital has an incentive to attract more patients by inducing a lower quality provision from the competing hospital, and this can be achieved by *underinvesting* at the first stage of the game. Such an incentive exists if the hospitals are sufficiently profit-oriented.

However, if the hospitals are sufficiently altruistic, so that the price-cost margin is negative in equilibrium, the investment incentives are the exact opposite. In this case, each hospital has an incentive to *reduce* demand (from unprofitable patients) by inducing a higher quality provision from the competing hospital, which can be achieved by *overinvesting* at the first stage. Notice, however, that since both hospitals have the same unilateral incentive to use the investment decision to strategically affect quality provision, these incentives cancel each other in equilibrium, leaving equilibrium quality provision unchanged.

Lemma 2 *Suppose that investment and quality are (weak) complements in the health benefit and cost functions, and that the price-cost margin is weakly increasing in investments: (i)* $b^{Iq} \geq 0$*, (ii)* $c^{Iq} \leq 0$ *and (iii)* $\partial p(I^{**})/\partial I - \left(c^{I} + c^{Iq}q^{**}\right) \geq 0$*. If at least one of the inequalities in (i)-(iii) is strict, then investment and quality provision are both lower (higher) in the sequential game if* $\alpha < (>) \widehat{\alpha}$*.*

Similar to the benchmark case, assumptions (i)-(iii) in Lemma 2 ensure that there is strategic complementarity between own investment and rival's quality provision, i.e. $\partial q_j \left(I^{**}\right) / \partial I_i > 0$. This implies that the hospital's incentives for under- or overinvestment are qualitatively the same as in the benchmark case (cf. Lemma 1). However, in contrast to the benchmark case, the introduction of these assumptions implies that investment and quality are equilibrium complements, i.e., $\partial V_q(I^{**}, q^{**})/\partial I > 0$, which implies that the strategic investment effect also affects equilibrium quality provision. More specifically, higher (lower) investments also imply higher (lower) equilibrium quality provision. Thus, depending on the degree of hospital altruism, investment and quality are either both higher or both lower in the sequential game.

Notice that only one of the assumptions in (i)-(iii) is needed in order to produce the results given by Lemma 2 (given that the other assumptions are as in the benchmark case of Lemma 1). One example that fits this case is laparoscopic (less invasive) surgery, which improves health outcomes for a given treatment quality and reduces treatment costs, and accordingly the marginal cost of quality provision.

Lemma 3 *Suppose that investment and quality are substitutes in the health benefit and cost func-*

tions ($b^{Iq} < 0$ and $c^{Iq} > 0$), and that the price-cost margin is decreasing in investments ($\partial p(I^{**})/\partial I - \left(c^I + c^{Iq}q^{**}\right) < 0$). Suppose also that all of these effects are 'small' in magnitude. In this case, in the sequential game hospitals underinvest while overproviding quality if $\alpha < \widehat{\alpha}$ and overinvest while underproviding quality if $\alpha > \widehat{\alpha}$.

This case differs from the previous one in that investment and quality are equilibrium substitutes, implying that overinvestment will be accompanied by underprovision of quality, while underinvestment will lead to overprovision of quality. Notice that for investment and quality to be equilibrium substitutes, it is enough to have $b^{Iq} < 0$ *or* $c^{Iq} > 0$ *or* $\partial p(I^{**})/\partial I - \left(c^I + c^{Iq}q^{**}\right) < 0$, given that other assumptions are as in the benchmark case. As long as all of these effects are sufficiently small, strategic complementarity between own investment and rival's quality remains, which implies that the investment incentives are as in the benchmark case.

Lemma 4 *Suppose that investment and quality are substitutes in the health benefit and cost functions ($b^{Iq} < 0$ and $c^{Iq} > 0$), and that the price-cost margin is decreasing in investments ($\partial p(I^{**})/\partial I - \left(c^I + c^{Iq}q^{**}\right) < 0$). Suppose also that at least one of these effects is 'large' in magnitude. In this case, in the sequential game hospitals overinvest while underproviding quality if $\alpha < \widehat{\alpha}$ and underinvest while overproviding quality if $\alpha > \widehat{\alpha}$.*

In our final case considered, we assume that the degree of benefit or cost substitutability between investment and quality is so large that the strategic nature of the game changes, making own investment and rival's quality strategic substitutes, i.e., $\partial q_j \left(I^{**}\right)/\partial I_i < 0$. Alternatively, strategic substitutability could also arise if investments have a sufficiently large negative effect on the price-cost margin, for example investments that lead to considerably higher treatment costs. This changes the strategic investment incentives relative to the benchmark case. If the hospitals are sufficiently profit-oriented, so that the equilibrium price-cost margin is positive, each hospital has an incentive to invest more in order to induce lower quality from the rival hospital at the quality competition stage. The opposite incentives apply if the price-cost margin is negative, which requires that the hospitals are sufficiently altruistic. As in the case considered by Lemma 3, the incentives for quality provision follow from the fact that investment and quality are equilibrium substitutes.

The special cases covered by Lemma 1-4 are summarised in Table 1.

Table 1. Comparison of equilibria under simultaneous and sequential choices

	$\frac{\partial(p-c)}{\partial I}$	b^{Iq}	c^{Iq}	$\frac{\partial q_j}{\partial I_i}$	$\frac{\partial V_q}{\partial I}$	If $\alpha < \widehat{\alpha}$:	If $\alpha > \widehat{\alpha}$:
(I)	0	0	0	> 0	0	$I^{**} < I^*$, $q^{**} = q^*$	$I^{**} > I^*$, $q^{**} = q^*$
(II)	> 0	> 0	< 0	> 0	> 0	$I^{**} < I^*$, $q^{**} < q^*$	$I^{**} > I^*$, $q^{**} > q^*$
(III)	< 0 (s)	< 0 (s)	> 0 (s)	> 0	< 0	$I^{**} < I^*$, $q^{**} > q^*$	$I^{**} > I^*$, $q^{**} < q^*$
(IV)	< 0 (l)	< 0 (l)	> 0 (l)	< 0	< 0	$I^{**} > I^*$, $q^{**} < q^*$	$I^{**} < I^*$, $q^{**} > q^*$

s = 'small' in absolute value; l = 'large' in absolute value

6 Social Welfare

In this section we present a welfare analysis in two parts. In the first part, we adopt a normative approach. We derive the first-best solution and show how this solution could be implemented through an optimal design of the payment contract. In the second part, we take a more positive approach by acknowledging that hospital payment schemes are often based on average-cost pricing rules and are unlikely to coincide with the optimal ones that maximise welfare. In this second part we analyse instead the welfare effects of several plausible policy reforms, which we define as switching between different types of hospital payment schemes that we observe across countries.

As the basis of our analysis in this section, we define social welfare, denoted by W, as the difference between aggregate patient utility and providers' costs, given by

$$W(I_i, I_j, q_i, q_j) = \varpi - \sum_{i=1}^{2} C(D_i, I_i, q_i). \tag{24}$$

where

$$\varpi = \int_0^{D_i(I_i,I_j,q_i,q_j)} (v + B(I_i, q_i) - tx)\, dx + \int_{D_i(I_i,I_j,q_i,q_j)}^1 (v + B(I_j, q_j) - t\,(1-x))\, dx. \tag{25}$$

is aggregate patient utility.

6.1 The first-best solution

Suppose that a welfarist regulator is able to choose investment, quality and demand for each hospital. Since the model is symmetric and aggregate transportation costs are minimised when each patient attends the nearest hospital, the first-best solution must necessarily be symmetric with equal investment and quality provision for each provider. Imposing symmetry, social welfare can be expressed as

$$W(I,q) = v + B(I,q) - \frac{t}{4} - c(I,q) - 2k(I). \tag{26}$$

Maximising (26) with respect to service quality and investment, we obtain the first best solution, denoted by (q^s, I^s), and implicitly given by[6]

$$\frac{\partial W(I,q)}{\partial q} = b^q + b^{Iq}I^s - \left(2c^q q^s + c^{Iq}I^s\right) = 0, \tag{27}$$

$$\frac{\partial W(I,q)}{\partial I} = b^I + b^{Iq}q^s - \left(c^I + c^{Iq}q^s\right) - 2\frac{\partial k(I^s)}{\partial I} = 0. \tag{28}$$

The socially optimal levels of investment and quality are characterised by the standard condition that marginal benefits equal marginal costs. The investment and quality levels given by (27)-(28) can be implemented as an equilibrium outcome by an appropriate design of the hospital payment scheme. However, the optimal payment contract depends on the characteristics of the game played by the hospitals, i.e., whether investment and quality decisions are made simultaneously or sequentially. A comparison of (27)-(28) with (10)-(11) and (19)-(20), respectively, allows us to reach the following conclusions:

Proposition 3 *(i) If investment and quality decisions are made simultaneously, the first-best solution can be implemented by a payment contract* $\left\{\widehat{p}\left(I_i\right), \widehat{T}\left(I_i\right)\right\}$*, where*

$$\widehat{p}\left(I^*\right) = c\left(I^*, q^*\right) + (1-2\alpha)t = c\left(I^s, q^s\right) + (1-2\alpha)t, \tag{29}$$

and

$$\frac{\partial \widehat{p}}{\partial I_i} = \frac{\partial \widehat{T}}{\partial I_i} = 0, \tag{30}$$

with (I^*, q^*) *implicitly given by (10)-(11).*

[6] Second order conditions are provided in Appendix A3.

(ii) If investment and quality decisions are made sequentially, the first-best solution can be implemented by a payment contract $\left\{\widetilde{p}(I_i), \widetilde{T}(I_i)\right\}$*, where*

$$\widetilde{p}(I^{**}) = c(I^{**}, q^{**}) + (1-2\alpha)t = c(I^s, q^s) + (1-2\alpha)t, \tag{31}$$

and

$$2\frac{\partial \widetilde{T}(I^{**})}{\partial I_i} + \frac{\partial \widetilde{p}(I^{**})}{\partial I_i} = (1-2\alpha)\left(b^q + b^{Iq} I^{**}\right)\frac{\partial q_j(I^{**})}{\partial I_i}, \tag{32}$$

with (I^{**}, q^{**}) *implicitly given by (19)-(20) and* $\partial q_j(I^{**})/\partial I_i$ *given by (21).*

The first part of the proposition shows that, if hospitals make investment and quality decisions simultaneously, the first-best solution can be implemented by a very simple payment contract that just specifies an appropriate level of the per-treatment price. If this price is set at the level given by (29), the hospitals will both invest and provide quality at the first-best level. Thus, it is possible for the regulator to kill two birds with one stone, and no other regulatory instruments are needed to achieve the first-best outcome.

The intuition for this result is the following. The optimal first-best quality and investment depend on their marginal patient benefits, $\partial B/\partial q_i$ and $\partial B/\partial I_i$, respectively. The equilibrium quality and investment, on the other hand, depend *inter alia* on how strongly demand responds to changes in quality and investment. However, the demand responsiveness to quality and investment also depend on their respective marginal patient benefits. Thus, both the first-best and the equilibrium levels of quality and investment are proportional to their marginal patient benefits. Moreover, since the degree of demand responsiveness of both quality and investment depends on the same transportation cost parameter, t, which we can interpret as an inverse measure of competition intensity, the providers' incentives for providing quality relative to investment are exactly proportional to the social planner's relative valuation of quality and investment, for any given treatment price p. The regulator can therefore vary the price to stimulate both quality and investment proportionally up to the first best levels.

As intuitively expected, and as seen from (29), the optimal price is inversely proportional to the degree of provider altruism. The first-best solution is implemented with a price above (below) marginal treatment costs if α is below (above) one half. How the optimal price depends on competition intensity also depends on the degree of altruism. If the degree of altruism is relatively low ($\alpha < 1/2$), so that the price-cost margin in the first-best solution is positive, more competition stimulates investments and quality provision and the optimal price must therefore be adjusted downwards. On the other hand, if the degree of altruism is sufficiently high ($\alpha > 1/2$), increased competition leads to a reduction in quality provision and investments because of a negative price-cost margin, which implies that the optimal price must be adjusted upwards in order to preserve the first-best outcome.

The conclusion that the optimal payment contract only needs to specify the per-treatment price no longer holds if investment and quality decisions are made sequentially. In this case, the price p that induces the first-best level of quality will lead to either under- or overinvestment, where the conditions for one or the other to occur are given by Proposition 1. Thus, the hospitals' inability to commit to a particular level of quality provision can be identified as a source of inefficiency which necessitates a richer set of regulatory tools in order to implement the first-best outcome. The optimal payment contract must therefore be complemented by at least one more instrument which incentivises investments separately. This can be done by making either the lump-sum payment or the per-treatment price dependent on investment; i.e., $\partial T/\partial I_i \neq 0$ or $\partial p/\partial I_i \neq 0$.[7]

Notice that the optimal per-treatment price (at equilibrium) remains the same under the sequential game and the simultaneous game, while it is the dependence of the per-treatment price or the lump-sum payment on investment which allows to correct for possible under- or over-investment under the sequential game. To further illustrate this result, suppose that the payment contract is such that both the per-treatment price and the lump-sum transfer are linear in investment, i.e., $p(I_i) = p_0 + p_1 I_i$ and $T(I_i) = T_0 + T_1 I_i$. The first-best solution can then be implemented in two different ways. (i) A simple optimal payment rule is such that $\widehat{p}_0 = \widetilde{p}_0 = c(I^s, q^s) + (1-2\alpha)t$ and $\widehat{p}_1 = \widetilde{p}_1 = 0$, for both the simultaneous and the sequential game. Instead, this optimal payment involves $\widehat{T}_1 = 0$ for the simultaneous game, and $\widetilde{T}_1 = (1/2 - \alpha)\left(b^q + b^{Iq} I^s\right)\left(\partial q_j(I^s)/\partial I_i\right)$ in the sequential game. This payment involves only a fixed per-treatment price under both games, and a lump-sum transfer which either increases or decreases in investment under the sequential game. (ii) An alternative optimal payment is such that $\widehat{p}_0 = c(I^s, q^s) + (1-2\alpha)t$ and $\widehat{p}_1 = \widehat{T}_1 = 0$ under the simultaneous game, whereas $\widetilde{p}_0 = c(I^s, q^s) + (1-2\alpha)t - \widetilde{p}_1 I^s$, $\widetilde{p}_1 = (1-2\alpha)\left(b^q + b^{Iq} I^s\right)\left(\partial q_j(I^s)/\partial I_i\right)$ and $\widetilde{T}_1 = 0$ under the sequential game. This payment still involves only a fixed per-treatment price under the simultaneous game, but a per-treatment price which either increases or decreases in investment in the sequential game. More specifically, this payment scheme implies $\widetilde{p}_0 \neq \widehat{p}_0$ and

[7] Some countries, such as France, Italy and Poland, use a payment contract that implements two instruments, where the reimbursement of capital cost is separate from the DRG tariff.

$\widetilde{p}_1 \neq 0$ for $I_i \neq I^s$ and $\widetilde{p}_0 = \widehat{p}_0$ and $\widetilde{p}_1 = 0$ for $I = I^s$.

Exactly how the optimal payment scheme should be designed in relation to the investment component depends on the level of hospital altruism and on the strategic relationship between investment and quality. Suppose that own investment and rival's quality are strategic complements ($\partial q_j/\partial I_i > 0$). If in addition the hospitals are sufficiently profit oriented ($\alpha < 1/2$), the first-best payment scheme should include an investment subsidy to counteract hospital incentive to underinvest, either through the lump-sum directly ($\partial T/\partial I_i > 0$) or the per-treatment price ($\partial p/\partial I_i > 0$). On the other hand, if the hospitals are sufficiently altruistic ($\alpha > 1/2$), so that the price-cost margin is negative in equilibrium, the first-best outcome is achieved by *disincentivising* investment, for example by making T a decreasing function of I. The opposite results hold when investment and rival's quality are strategic substitutes. If the price-cost margin is positive, the first-best payment scheme disincentivises investment. If the price cost margin is negative, the payment scheme incentivises investment. Therefore, although our results are in general indeterminate, we can precisely characterise the optimal payment scheme as a function of the price-cost margin and the strategic relationship between quality and investment.

6.2 Policy options

In this section, we investigate three different policy options, which reflect observed differences in real-world payment schemes across different countries. To do so, without much loss of generality, we restrict the payment contract to the linear specifications $p(I_i) = p_0 + p_1 I_i$ and $T(I_i) = T_0 + T_1 I_i$. We also only focus on the (more realistic) sequential game solution, implying that welfare is measured by

$$W(I^{**}, q^{**}) = v + B(I^{**}, q^{**}) - \frac{t}{4} - c(I^{**}, q^{**}) - 2k(I^{**}). \quad (33)$$

6.2.1 Paying separately for investment

Consider a policy that introduces a payment rule which rewards investment in health technologies through the lump-sum payment to cover part or all of the capital costs, on top of the DRG per-treatment payment, which is line with arrangements in Germany, Ireland, Norway, Portugal and Spain (Quentin et al., 2011). Analytically, the payment rule before the policy is $p(I_i) = p_0$, $T(I_i) = \overline{T}_0$, and after the policy it is $p(I_i) = p_0$, $T(I_i) = \underline{T}_0 + T_1 I_i$, with $\overline{T}_0 > \underline{T}_0$ and $T_1 > 0$.

Given that changes in $\overline{T}_0$ and $\underline{T}_0$ have no effect on quality and investment, the only effect on welfare is driven by the introduction of T_1. Thus, we can assess the effect of the reform by applying the post-policy payment rule and doing comparative statics on T_1. Differentiating (33) with respect to T_1 yields

$$\frac{dW(I^{**},q^{**})}{dT_1} = \frac{\partial W(I^{**},q^{**})}{\partial I}\frac{\partial I^{**}}{\partial T_1} + \frac{\partial W(I^{**},q^{**})}{\partial q}\frac{\partial q^{**}}{\partial T_1}, \tag{34}$$

with

$$\frac{\partial I^{**}}{\partial T_1} = \frac{1}{\phi}\left[\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right)}{2t} + c^q\right] > 0, \tag{35}$$

$$\frac{\partial q^{**}}{\partial T_1} = \frac{V_{qI}}{\phi} \gtrless 0, \tag{36}$$

where the definitions of $\phi > 0$ and $V_{qI} \gtrless 0$, and further details, are given in Appendix A3.2.

The effect of the reform on the equilibrium level of investment is straightforward. A marginal increase in T_1 increases the marginal revenue of investment and therefore leads to higher investment. It also leads to higher service quality if investment and quality are complements ($V_{qI} > 0$), but to lower service quality if they are substitutes ($V_{qI} < 0$).

Suppose that, pre-reform, equilibrium investment and quality are *below* the first best level ($\partial W(I^{**},q^{**})/\partial I > 0$ and $\partial W(I^{**},q^{**})/\partial q > 0$). For example, this could arise if the DRG price is below the first-best level, $p_0 < \widetilde{p}(I^{**})$, there are no payments associated to additional hospital investments, $\partial \widetilde{T}(I^{**})/\partial I_i = \partial \widetilde{p}(I^{**})/\partial I_i = 0$, own investment and rival's quality are strategic complements ($\partial q_j/\partial I_i > 0$) and hospitals are sufficiently profit oriented. Then the introduction of a payment which incentivises investment separately is always welfare improving when investment and quality are complements ($V_{qI} > 0$), or if quality and investment are substitutes as long as the degree of substitutability is sufficiently small. This policy is also welfare improving if equilibrium investment is below the first best level and equilibrium quality is above the first best level (i.e., $\partial W(I^{**},q^{**})/\partial I > 0$ and $\partial W(I^{**},q^{**})/\partial q < 0$) if investments and qualities are substitutes ($V_{qI} < 0$) or if they are complements but the degree of complementarity is sufficiently small.

The results are reversed when investment and quality are *above* the first best level ($\partial W(I^{**},q^{**})/\partial I < 0$ and $\partial W(I^{**},q^{**})/\partial q < 0$). Then the introduction of a payment scheme which financially rewards investment is always welfare reducing if investment and quality are complements, or if they are substitutes but the degree of substitutability is sufficiently small. The policy is still welfare reducing when equilibrium investment is above the first best level and equilibrium quality is below the first best level (i.e., $\partial W(I^{**}, q^{**})/\partial I < 0$ and $\partial W(I^{**}, q^{**})/\partial q > 0$), if investment and quality are substitutes, or if they are complements but the degree of complementarity sufficiently small.

In summary, the effect of a policy that pays separately for investment is driven by whether investment levels are above or below the first best level under two different scenarios: (i) indirect welfare effects through changes in service quality are sufficiently small or (ii) the quality welfare effects go in the same direction as the investment welfare effects.

6.2.2 Paying for investment through a higher DRG price

Consider a policy which replaces a payment rule where investment is paid through a separate lump-sum payment with one that includes payment for capital costs exclusively through the DRG per-treatment payment, like in countries such as Austria, England, Estonia, Finland, Netherlands, Sweden and Switzerland (Scheller-Kreinsen et al., 2011). Analytically, before the policy the payment rule is $p(I_i) = \underline{p}_0$, $T(I_i) = T_0$, and after the reform it is $p(I_i) = \overline{p}_0$, $T(I_i) = 0$, with $\overline{p}_0 > \underline{p}_0$ and $T_0 > 0$. Given that changes in T_0 have no effect on quality and investment, the only effect on welfare is driven by the increase in the DRG tariff. We can therefore assess the effects of this policy reform by doing comparative statics on p_0. Differentiating (33) with respect to p_0 yields

$$\frac{dW(I^{**}, q^{**})}{dp_0} = \frac{\partial W(I^{**}, q^{**})}{\partial I}\frac{\partial I^{**}}{\partial p_0} + \frac{\partial W(I^{**}, q^{**})}{\partial q}\frac{\partial q^{**}}{\partial p_0}, \tag{37}$$

with

$$\frac{\partial I^{**}}{\partial p_0} = \frac{1}{2t\phi}\left[\left(b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right)\left(-V_{qq}\right) + V_{Iq}\left(b^q + b^{Iq}I^{**}\right)\right], \tag{38}$$

$$\frac{\partial q^{**}}{\partial p_0} = \frac{1}{2t\phi}\left[\left(b^q + b^{Iq}I^{**}\right)\left(-V_{II}\right) + V_{qI}\left(b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right)\right], \tag{39}$$

and where the expressions for $V_{II} < 0$, $V_{qq} < 0$, $V_{qI} \gtrless 0$ and $V_{Iq} \gtrless 0$ are given in Appendix A3.2.

A higher DRG tariff has a direct positive effect on the marginal revenue of service quality, given by the first term in the square brackets of (39). A similar positive effect applies to the marginal revenue of investment, but here there is also an additional effect related to the strategic incentive to affect the rival hospital's quality provision through own investment. The sum of these two effects is given by the first term in the square brackets of (38), where the sign of the additional (strategic) effect depends on the sign of $\partial q_j (I^{**}) / \partial I_i$. More specifically, a higher DRG tariff increases the profit margin and therefore reinforces the incentive to increase (reduce) own investment in order to induce a reduction in the rival's quality provision if own investment and rival's quality are strategic substitutes (complements). Finally, there are also indirect effects determined by how a quality increase affects the marginal incentives for investment (V_{Iq}) and how higher investments affect the marginal incentives for quality provision (V_{qI}).

If we assume that the latter effects are sufficiently small (i.e, that the effects through V_{qI} and V_{Iq} are second-order effects), then an increase in the DRG tariff increases the marginal revenue of both investment and service quality, yielding $\partial I^{**}/\partial p_0 > 0$ and $\partial q^{**}/\partial p_0 > 0$, if own investment and rival's quality are strategic substitutes ($\partial q_j (I^{**}) / \partial I_i < 0$). This also holds if own investment and rival's quality are strategic complements, as long the degree of strategic complementarity is sufficiently small. If the equilibrium investment and quality are *below* the first best level, then this policy is always welfare improving. Analogously, if they are *above* the first best level, the policy is welfare reducing. If either equilibrium investment or quality is above the first best level with the other variable being below the first best level, then the overall effect of this policy reform is in general indeterminate.

6.2.3 Incentivising investment through refinements in DRG pricing

Finally, consider a policy which incentivises investment through the per-treatment price, in the sense that higher investments imply a higher DRG tariff. Several health systems have introduced a 'new DRG' in the form of an additional DRG price associated with a new technology, that effectively leads to a higher per-treatment price whenever the new technology is adopted. Examples include coronary stents in Australia, Austria, Canada, England, Germany, Japan and the United States (Hernandez et al., 2015; Sorenson et al., 2013, 2015), and transcatheter aortic-valve implantation (TAVI) in France, intracranial neurostimulators in Portugal, and Implantable cardioverter-defibrillator in Italy (Sorenson et al., 2015; Cappellaro et al., 2009). Analytically, before the policy the payment rule is $p(I_i) = p_0$, $T(I_i) = \overline{T}_0$, and after the reform it is $p(I_i) = p_0 + p_1 I_i$, $T(I_i) = \underline{T}_0$, with $\overline{T}_0 > \underline{T}_0$. Given that changes in T_0 have no effect on quality and investment, the only effect on welfare is driven by the increase in the DRG tariff. We can therefore assess the welfare effect of this policy by considering a marginal increase in p_1. Differentiating (33) with respect to p_1 yields

$$\frac{dW(I^{**},q^{**})}{dp_1} = \frac{\partial W(I^{**},q^{**})}{\partial I}\frac{\partial I^{**}}{\partial p_1} + \frac{\partial W(I^{**},q^{**})}{\partial q}\frac{\partial q^{**}}{\partial p_1}, \tag{40}$$

with

$$\frac{\partial I^{**}}{\partial p_1} = \frac{1}{\phi}\left(V_{Ip_1}\left(-V_{qq}\right) + I^{**}\frac{V_{Iq}\left(b^q + b^{Iq}I^{**}\right)}{2t}\right), \tag{41}$$

$$\frac{\partial q^{**}}{\partial p_1} = \frac{1}{\phi}\left(I^{**}\frac{\left(b^q + b^{Iq}I^{**}\right)\left(-V_{II}\right)}{2t} + V_{qI}V_{Ip_1}\right), \tag{42}$$

and

$$V_{Ip_1} = I^{**}V_{Ip_0} + \frac{1}{2} - \frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right)^3}{8t^3\Delta}\left(p(I^{**}) - c(I^{**},q^{**})\right) \gtrless 0, \tag{43}$$

where $\Delta > 0$ is given by (A26) in Appendix A2.3 and

$$V_{Ip_0} = \frac{1}{2t}\left[b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right] \gtrless 0. \tag{44}$$

is the effect of a marginal increase in p_0 on investment incentives for a given quality level.

This particular policy affects incentives for investment and quality provision in two different ways. First, it implies an increase in the DRG price level. This means that the direct effect on the marginal revenue of *quality* provision is similar to the policy in the previous section (the first term in (39) is similar to the first term in (42)). The direct effects on *investment* incentives are also present under this policy, and captured by the first term in (43). However, incentivising investment through a refinement of DRG pricing yields *two additional effects* on the marginal revenue of investment, given by the second and third terms in (43). Both of these additional effects result from the fact that an increase in p_1 implies that investments have a stronger positive effect on the price-cost margin. Firstly, this directly strengthens the incentive for investment. Secondly, this also implies that the effect of own investment on rival's quality increases, as explained in Section 5.1.[8] In other words, the strategic complementarity is reinforced (or the strategic substitutability is weakened) between own investment and rival's quality. All else equal, this effect leads to weaker (stronger) investment incentives if the equilibrium price-cost margin is positive (negative). Finally, and similarly to the

[8] It follows from (21) that

$$\frac{\partial}{\partial p_1}\left(\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right) = \frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right)^2}{4t^2\Delta} > 0.$$

previous policy, the overall effects of the policy are also determined by how a quality change affects the marginal incentives for investment (V_{Iq}) and *vice versa* (V_{qI}). Once more, it seems reasonable to assume that the latter effects are second-order effects and that the sign of the overall effects are primarily determined by the direct effects described above.

Based on the direct effects, incentivising investment through the DRG price leads to higher quality provision while, perhaps surprisingly, the effect on investment is *a priori* indeterminate. Sufficient (but not necessary) conditions for this payment scheme to stimulate investment are that (i) own investment and rival's quality are strategic substitutes ($\partial q_j\left(I^{**}\right)/\partial I_i < 0$) and (ii) providers are sufficiently altruistic, such that the price-cost margin is negative in equilibrium. On the contrary, if own investment and rival's quality are strategic complements and providers are profit oriented, incentivising investment through the DRG price might possibly *reduce* investments due to each provider's incentive to strategically affect the rival's quality provision through own investment.

As before, the overall welfare effect of the reform depends crucially on whether quality and investments are below or above the first-best levels prior to the policy. In the former case (i.e., $\partial W(I^{**}, q^{**})/\partial q > 0$ and $\partial W(I^{**}, q^{**})/\partial I > 0$), the policy will unambiguously increase welfare if $\partial I^{**}/\partial p_1 > 0$ and $\partial q^{**}/\partial p_1 > 0$. On the other hand, if the policy is counterproductive in terms of stimulating investment incentives ($\partial I^{**}/\partial p_1 < 0$), which is a theoretical possibility as explained above, then it has an unambiguously positive effect on welfare only if the pre-policy equilibrium is characterised by underprovision of service quality but overinvestment in medical technology.

7 Concluding remarks

Hospital investments in medical innovations and new technologies can affect both health outcomes and provider costs. This study has investigated how hospitals make investment decisions, and the circumstances under which they lead to under- or overinvestment, and how these investment decisions affect the provision of service quality under a range of payment arrangements. Although the results are generally indeterminate, we can characterise them in a precise way. We show that hospitals underinvest if (i) own investment and the quality of the competing hospital are strategic complements and the price-cost margin is positive or (ii) own investment and quality are strategic substitutes and the price-cost margin is negative. Instead hospitals overinvest in the reversed scenarios (investment and quality are strategic complements and price-cost margin is negative;

strategic substitution and positive price-cost margin).

In terms of optimal price regulation, we show that the regulator must complement the per-treatment price with at least one more instrument to correctly incentivise investments, either through a separate payment which rewards investment or a treatment price which depends on investment. The results mirror our key findings. The regulator has to incentivise investment when (i) investment and quality are strategic complements and the provider works at a positive price cost-margin, or (ii) investment and quality are strategic substitutes and the provider works at a negative price cost margin.

In terms of policy implications, our analysis informs possible policy interventions under current activity-based payment arrangements that set, in most countries, prices at the average cost instead of relating them to marginal costs as prescribed by optimal regulation theory. We show that the introduction of a policy with a separate payment which directly incentivises investment, commonly used in several countries, can be welfare improving if investment and quality are initially below the first-best levels and investment and quality are complements or if they are substitutes but the degree of substitutability is sufficiently small. This is also the case if investment is below and quality is above the first-best levels, and investment and quality are either substitutes or sufficiently weak complements. In other scenarios, the introduction of this payment rule will create trade-offs between the welfare effects arising from changes in investment and quality.

Some countries pay for investment through a higher activity-based tariff per patient treated, while others through a separate funding scheme. We show that the former is welfare improving if investment and quality are below the first-best level and a higher DRG tariff increases the marginal revenue of both investment and service quality. However, this may not be the case if either investment or quality is above the first-best level, so that a trade-off arises. Finally, we find that a policy incentivising investment through refinements of DRG pricing (so that additional investments are rewarded with a higher per unit price) stimulates quality provision while the effect on investment is, perhaps surprisingly, *a priori* ambiguous. In this case, even if both quality and investment are below the first-best level, a trade-off arises between the welfare gain from higher quality and welfare loss from lower investment.

Our analysis highlights the role of two main factors. The first is whether providers work at a positive or negative price-cost margin. This is likely to depend on the health system, with systems with fewer beds per capita and higher capacity constraints more likely to work a negative price-cost margin. This may also be the case for countries that use mixed payment systems. For example, in Norway activity-based payment only covers about 50-60% of average costs, with the rest being covered by a capitation arrangement. There are also discussions in England of moving towards 'blended' payment systems with the activity-based payment accounting for as little as 30% (Appleby et al., 2012). Future empirical work on empirical estimates of marginal treatment costs could also quantify the size of price-cost margins.

A second key factor is whether investment and quality are complements or substitutes for each provider, or strategic complements or substitutes across providers. This is also an area that could be informed by future empirical work. For example, it would be useful to estimate whether an exogenous increase in hospital investments lead to an increase (complementarity) or a reduction (substitution) in service provision by the same provider, as these effects play an important role in the welfare analysis of policy interventions. Perhaps even more important, but also empirically challenging, would be to investigate how changes in provider investment affect the quality of rival providers. These could be explored using a spatial econometrics approach similar to the one adopted to investigate whether the qualities are strategic complements or substitutes (Gravelle et al., 2014; Longo et al., 2017).

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Appendix

This appendix contains second-order conditions and supplementary calculations for each part of the analysis, where the content of Appendix A1, A2 and A3 complements the analysis of Section 4, 5 and 6, respectively.

A1. Simultaneous game

The second-order conditions of the hospital are given by

$$\frac{\partial^2 V_i(q_i,q_j,I_i,I_j)}{\partial q_i^2} = -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} - 2c^q D_i < 0, \tag{A1}$$

$$\frac{\partial^2 V_i(q_i,q_j,I_i,I_j)}{\partial I_i^2} = \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^I + b^{Iq} q_i}{t} + \frac{\partial^2 p(I_i)}{\partial I_i^2} D_i + \frac{\partial^2 T(I_i)}{\partial T_i^2} - \frac{\partial^2 k(I_i)}{\partial I_i^2} < 0, \tag{A2}$$

and

$$\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_i}{\partial I_i^2} - \left(\frac{\partial^2 V_i}{\partial I_i \partial q_i}\right)^2 \geq 0, \tag{A3}$$

where $\partial^2 V_i / \partial I_i \partial q_i$ is given by (A13) below. These conditions are satisfied if $k(I_i)$ is sufficiently convex.

A2. Sequential game

A2.1 Derivation of (12) and (13)

The optimality conditions of quality, $\partial V_i (I_i, I_j, q_i, q_j) / \partial q_i = 0$ and $\partial V_j (I_i, I_j, q_i, q_j) / \partial q_j = 0$, are given more explicitly by

$$\begin{aligned}\left(b^q + b^{Iq} I_i\right)\left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] - \left(2c^q q_i + c^{Iq} I_i\right) D_i(I_i, I_j, q_i, q_j) &= 0, & \text{(A4)}\\ \left(b^q + b^{Iq} I_j\right)\left[\alpha + \frac{p(I_j) - c(I_j, q_j)}{2t}\right] - \left(2c^q q_j + c^{Iq} I_j\right) D_j(I_i, I_j, q_i, q_j) &= 0. & \text{(A5)}\end{aligned}$$

Totally differentiating these conditions with respect to I_i, we obtain

$$\begin{bmatrix} \frac{\partial^2 V_i}{\partial q_i^2} & \frac{\partial^2 V_i}{\partial q_i \partial q_j} \\ \frac{\partial^2 V_j}{\partial q_j \partial q_i} & \frac{\partial^2 V_j}{\partial q_j^2} \end{bmatrix} \begin{bmatrix} dq_i \\ dq_j \end{bmatrix} + \begin{bmatrix} \frac{\partial^2 V_i}{\partial q_i \partial I_i} \\ \frac{\partial^2 V_j}{\partial q_j \partial I_i} \end{bmatrix} dI_i = 0, \tag{A6}$$

which gives

$$\frac{dq_i}{dI_i} = \frac{-\frac{\partial^2 V_i}{\partial q_i \partial I_i}\frac{\partial^2 V_j}{\partial q_j^2} + \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial I_i}}{\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j^2} - \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial q_i}}, \tag{A7}$$

$$\frac{dq_j}{dI_i} = \frac{-\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j \partial I_i} + \frac{\partial^2 V_j}{\partial q_j \partial q_i}\frac{\partial^2 V_i}{\partial q_i \partial I_i}}{\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j^2} - \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial q_i}}, \tag{A8}$$

where

$$\frac{\partial^2 V_i}{\partial q_i^2} = -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} - 2c^q D_i < 0. \tag{A9}$$

$$\frac{\partial^2 V_j}{\partial q_j^2} = -\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} - 2c^q D_j < 0, \tag{A10}$$

$$\frac{\partial^2 V_i}{\partial q_i \partial q_j} = \frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_j\right)}{2t} > 0, \tag{A11}$$

$$\frac{\partial^2 V_j}{\partial q_j \partial q_i} = \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t} > 0, \tag{A12}$$

$$\begin{aligned} \frac{\partial^2 V_i}{\partial q_i \partial I_i} = {} & b^{Iq}\left(\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right) + \left(\frac{\partial p}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \\ & - \left(2c^q q_i + c^{Iq} I_i\right)\frac{b^I + b^{Iq} q_i}{2t} - c^{Iq} D_i, \end{aligned} \tag{A13}$$

$$\frac{\partial^2 V_j}{\partial q_j \partial I_i} = \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t} > 0. \tag{A14}$$

Denote by Δ the denominator in (A7) and (A8), which is given by

$$\begin{aligned} \Delta = {} & \left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} + 2c^q D_i\right)\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right) \\ & - \left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_j\right)}{2t}\right)\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t}\right). \end{aligned} \tag{A15}$$

By rearranging and factorising some terms, we obtain

$$\Delta = \frac{1}{4t^2}\left(\begin{array}{c} 3\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right) \\ +8tc^q \left(\begin{array}{c} D_j\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right) \\ +D_i\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right) + 2tc^q D_i D_j \end{array}\right) \end{array}\right) \tag{A16}$$

The numerator in (A7) is

$$\begin{aligned} & -\frac{\partial^2 V_i}{\partial q_i \partial I_i}\frac{\partial^2 V_j}{\partial q_j^2} + \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial I_i} \\ = & \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} b^{Iq}\left(\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right) - \left(2c^q q_i + c^{Iq} I_i\right)\frac{b^I + b^{Iq} q_i}{2t} \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} - c^{Iq} D_i \end{array}\right] \\ & + \frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_j\right)}{2t}\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t}. \end{aligned} \tag{A17}$$

Using the first-order condition optimal quality, (8), and re-arranging, we obtain

$$\begin{aligned} & -\frac{\partial^2 V_i}{\partial q_i \partial I_i}\frac{\partial^2 V_j}{\partial q_j^2} + \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial I_i} \\ = & \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \\ & - \frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j\right). \end{aligned} \tag{A18}$$

Therefore, by substitution, (12) is given by

$$\frac{dq_i}{dI_i} = \frac{1}{\Delta}\left(\begin{array}{c} \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \\ - \frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j\right) \end{array}\right), \tag{A19}$$

To derive $\frac{dq_j}{dI_i}$, note that the numerator in (A8) is

$$
\begin{aligned}
& -\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j \partial I_i}+\frac{\partial^2 V_j}{\partial q_j \partial q_i}\frac{\partial^2 V_i}{\partial q_i \partial I_i} \\
= & \left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} + 2c^q D_i\right)\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t}\right) \\
& +\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t}\left[\begin{array}{c} b^{Iq}\left(\alpha + \frac{p(I_i)-c(I_i,q_i)}{2t}\right) + \left(\frac{\partial p}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \\ -\left(2c^q q_i + c^{Iq} I_i\right)\frac{b^I + b^{Iq} q_i}{2t} - c^{Iq} D_i \end{array}\right].
\end{aligned}
\tag{A20}
$$

Using the first-order condition for optimal quality, (8), and rearranging some terms, (A20) reduces to

$$
\begin{aligned}
& -\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j \partial I_i}+\frac{\partial^2 V_j}{\partial q_j \partial q_i}\frac{\partial^2 V_i}{\partial q_i \partial I_i} \\
= & \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t}\left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{2t} + c^q D_i\right) \\
& +\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t}\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ +\left(\frac{\partial p}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right].
\end{aligned}
\tag{A21}
$$

Therefore, (13) is obtained by

$$
\frac{dq_j}{dI_i} = \frac{1}{\Delta}\left(\begin{array}{c} \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t}\left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{2t} + c^q D_i\right) + \\ \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t}\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ +\left(\frac{\partial p}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \end{array}\right).
\tag{A22}
$$

A2.2 Second order condition

In the investment game, the second order condition is given by

$$
\frac{\partial^2 V_i}{\partial I_i^2} = \left\{\begin{array}{c} \frac{dq_i}{dI_i}\left(b^{Iq}\left(\alpha + \frac{p(I_i)-c(I_i,q_i)}{2t}\right) - c^{Iq} D_i - \frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{2t}\right) \\ +\frac{\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right) + \frac{\partial^2 p(I_i)}{\partial I_i^2} D_i + \frac{\partial^2 T(I_i)}{\partial I_i^2} - \frac{\partial^2 k(I_i)}{\partial I_i^2} \\ +\frac{\partial p(I_i)/\partial I_i - \left(c^I + c^{Iq} q_i\right)}{2t}\left[\frac{dq_i}{dI_i}\left(b^q + b^{Iq} I_i\right) - \frac{dq_j}{dI_i}\left(b^q + b^{Iq} I_j\right)\right] \\ -\Upsilon\frac{b^q + b^{Iq} I_j}{2t}\left[p(I_i) - c(I_i, q_i)\right] \end{array}\right\} < 0,
\tag{A23}
$$

where Υ is the derivative of 13 with respect to I_i. Define ψ as the numerator in 13. In this case

$\Upsilon = \left(\psi_{I_i}\Delta - \psi\Delta_{I_i}\right)/\Delta^2$, where

$$\psi_{I_i} = \frac{\left(2c^q q_j + c^{Iq} I_j\right)}{4t^2}\left(\begin{array}{c} \left(b^I + b^{Iq} q_i\right)\left[b^q c^{Iq} + 2b^{Iq}\left(c^q q_i + c^{Iq} I_i\right) + c^q\left(b^I + b^{Iq} q_i\right)\right] \\ +\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)\left(b^{Iq} - c^{Iq}\right) \\ +\left(b^q + b^{Iq} I_i\right)\left(\frac{\partial^2 p(I_i)}{\partial I_i^2}\left(b^q + b^{Iq} I_i\right) + 2b^{Iq}\left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\right) \end{array}\right) \quad (A24)$$

and

$$\Delta_{I_i} = \frac{1}{4t^2}\left(\begin{array}{c} 3\left(c^{Iq} b^q + 2b^{Iq}\left(c^q q_i + c^{Iq} I_i\right)\right)\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right) \\ +4c^q\left(\begin{array}{c} 2tD_j\left(c^{Iq} b^q + 2b^{Iq}\left(c^q q_i + c^{Iq} I_i\right)\right) \\ -\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right) \\ +\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right) + 2tc^q\left(b^I + b^{Iq} q_i\right)\left(D_j - D_i\right) \end{array}\right) \end{array}\right). \quad (A25)$$

The condition in (A23) holds if $k(I_i)$ is sufficiently convex.

A2.3 Symmetric equilibrium

The denominator in (A7) and (A8), denoted Δ, is given by

$$\Delta = \frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right)\left(3\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right) + 8tc^q\right) + \left(2tc^q\right)^2}{4t^2}. \quad (A26)$$

In the symmetric equilibrium, dq_i/dI_i and dq_j/dI_i are given by, respectively,

$$\frac{\partial q_i\left(I^{**}\right)}{\partial I_i} = \frac{1}{2\Delta}\left(\begin{array}{c} -\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^I + b^{Iq} q^{**}\right)}{t}\left(\frac{\left(b^q + b^{Iq} I^{**}\right)\left(2c^q q^{**} + c^{Iq} I^{**}\right)}{2t} + c^q\right) \\ +\left(\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right)}{t} + c^q\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)}{\left(b^q + b^{Iq} I^{**}\right)} - c^{Iq}\right) \\ +\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right)\right)\frac{b^q + b^{Iq} I^{**}}{t} \end{array}\right] \end{array}\right) \quad (A27)$$

and

$$\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}=\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{4t\Delta}\left(\begin{array}{c} c^q\left(b^I+b^{Iq}q^{**}\right) \\ +\left(b^q+b^{Iq}I^{**}\right)\left[\begin{array}{c}\left(b^{Iq}\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{\left(b^q+b^{Iq}I^{**}\right)}-c^{Iq}\right) \\ +\frac{\left(2c^q q+c^{Iq}I^{**}\right)\left(b^I+b^{Iq}q^{**}\right)}{t} \\ +\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^I+c^{Iq}q^{**}\right)\right)\frac{b^q+b^{Iq}I^{**}}{t}\end{array}\right]\end{array}\right). \tag{A28}$$

A3. Welfare Analysis

A3.1 Second order conditions

The second order conditions for first-best quality and investments are given by

$$\frac{\partial^2 W}{\partial q_i^2}=-2c^q<0, \tag{A29}$$

$$\frac{\partial^2 W}{\partial I_i^2}=-2\frac{\partial^2 k(I_i)}{\partial I_i^2}<0 \tag{A30}$$

and

$$\frac{\partial^2 W}{\partial q_i^2}\frac{\partial^2 W}{\partial I_i^2}-\left(\frac{\partial^2 W}{\partial q\partial I}\right)^2=4c^q\frac{\partial^2 k(I_i)}{\partial I_i^2}-\left(b^{Iq}-c^{Iq}\right)^2>0. \tag{A31}$$

These conditions hold if $k(I_i)$ is sufficiently convex.

A3.2 Comparative Statics

Considering the subgame-perfect Nash Equilibrium implicitly defined by (19)-(20), the comparative statics results reported in Section 6.2 are found by total differentiation of this system and the application of Cramer's rule. Using the notation $V_{xy}:=\partial V_x/\partial y$, we derive the following expressions:

$$\frac{\partial q^{**}}{\partial T_1}=\frac{-V_{qT_1}V_{II}+V_{qI}V_{IT_1}}{V_{qq}V_{II}-V_{Iq}V_{qI}}, \tag{A32}$$

$$\frac{\partial I^{**}}{\partial T_1}=\frac{-V_{qq}V_{IT_1}+V_{qT_1}V_{Iq}}{V_{qq}V_{II}-V_{Iq}V_{qI}}, \tag{A33}$$

$$\frac{\partial q^{**}}{\partial p_0}=\frac{-V_{qp_0}V_{II}+V_{qI}V_{Ip_0}}{\phi}, \tag{A34}$$

$$\frac{\partial I^{**}}{\partial p_0} = \frac{-V_{qq}V_{Ip_0} + V_{qp_0}V_{Iq}}{\phi}, \tag{A35}$$

$$\frac{\partial q^{**}}{\partial p_1} = \frac{-V_{qp_1}V_{II} + V_{qI}V_{Ip_1}}{\phi}, \tag{A36}$$

$$\frac{\partial I^{**}}{\partial p_1} = \frac{-V_{qq}V_{Ip_1} + V_{qp_1}V_{Iq}}{\phi}, \tag{A37}$$

where $\phi := V_{qq}V_{II} - V_{Iq}V_{qI} > 0$. The different terms in the numerators of (A32)-(A37) are defined as follows:

$$V_{qq} = -\frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right)}{2t} - c^q < 0 \tag{A38}$$

and

$$\begin{aligned} V_{II} \quad = \quad & \frac{\left(b^I + b^{Iq}q^{**}\right)}{2t}\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right) - \frac{\partial^2 k(I^{**})}{\partial I^2} \\ & -\Psi\frac{\left(b^q + b^{Iq}I^{**}\right)}{2t}\left[p(I^{**}) - c(I^{**}, q^{**})\right] \\ & -\frac{1}{2t}\left[\begin{array}{c} b^{Iq}\left(p(I^{**}) - c(I^{**}, q^{**})\right) + \\ \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right)\left(b^q + b^{Iq}I^{**}\right) \end{array}\right]\frac{\partial q_j\left(I^{**}\right)}{\partial I_i} < 0\ , \end{aligned} \tag{A39}$$

where Ψ is the derivative of (21) with respect to I. Defining Ξ as the numerator in (21), we have $\Psi = \left(\Xi_I\Delta - \Xi\Delta_I\right)/4t\Delta^2$, where the derivative of the denominator Δ with respect to I is given by

$$\Delta_I = \frac{\left[c^{Iq}b^q + 2b^{Iq}\left(c^q q^{**} + c^{Iq}I^{**}\right)\right]\left[3\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right) + 4tc^q\right]}{2t^2}, \tag{A40}$$

and the derivative of Ξ with respect to I, is given by

$$\begin{aligned} \Xi_I \quad = \quad & c^{Iq}\left(\begin{array}{c} c^q\left(b^I + b^{Iq}q^{**}\right) + b^{Iq}\left(2c^q q^{**} + c^{Iq}I^{**}\right) - c^{Iq}\left(b^q + b^{Iq}I^{**}\right) \\ +\frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^I + b^{Iq}q^{**}\right)\left(b^q + b^{Iq}I^{**}\right)}{t} \\ +\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right)\frac{\left(b^q + b^{Iq}I^{**}\right)^2}{t} \end{array}\right) \\ & + \left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(\begin{array}{c} \left(c^{Iq}b^q + 2b^{Iq}\left(c^q q^{**} + c^{Iq}I^{**}\right)\right)\frac{\left(b^I + b^{Iq}q^{**}\right)}{t} \\ +\frac{\partial^2 p(I^{**})}{\partial I^2}\frac{\left(b^q + b^{Iq}I^{**}\right)^2}{t} \\ +2b^{Iq}\left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq}q^{**}\right)\right)\frac{\left(b^q + b^{Iq}I^{**}\right)}{t} \end{array}\right). \end{aligned} \tag{A41}$$

Further:

$$V_{qI}=b^{Iq}\left(\frac{2c^{q}q^{**}+c^{Iq}I^{**}}{2\left(b^{q}+b^{Iq}I^{**}\right)}\right)+\frac{b^{q}+b^{Iq}I^{**}}{2t}\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^{I}+c^{Iq}q^{**}\right)\right)-\frac{c^{Iq}}{2}\lesseqgtr 0 \tag{A42}$$

and

$$\begin{aligned}V_{Iq} &= b^{Iq}\left(\frac{2c^{q}q^{**}+c^{Iq}I^{**}}{2\left(b^{q}+b^{Iq}I^{**}\right)}\right)+\frac{\left(2c^{q}q^{**}+c^{Iq}I^{**}\right)}{2t}\left(\left(b^{q}+b^{Iq}I^{**}\right)\frac{\partial q_{j}\left(I^{**}\right)}{\partial I_{i}}-\left(b^{I}+b^{Iq}q^{**}\right)\right)\\ &\quad -\frac{c^{Iq}}{2}-\Phi\frac{\left(b^{q}+b^{Iq}I^{**}\right)}{2t}\left(p(I^{**})-c(I^{**},q^{**})\right)\lesseqgtr 0,\end{aligned} \tag{A43}$$

where Φ is the derivative of (21) with respect to q and given by $\Phi=\left(\Xi_{q}\Delta-\Xi\Delta_{q}\right)/4t\Delta^{2}$, where the derivative of the denominator Δ in (21) with respect to q is given by

$$\Delta_{q}=\frac{c^{q}\left(b^{q}+b^{Iq}I^{**}\right)\left[3\left(2c^{q}q^{**}+c^{Iq}I^{**}\right)\left(b^{q}+b^{Iq}I^{**}\right)+4tc^{q}\right]}{t^{2}}, \tag{A44}$$

and the derivative of the numerator Ξ in (21) with respect to q, is given by

$$\begin{aligned}\Xi_{q} &= 2c^{q}\left(\begin{array}{c} c^{q}\left(b^{I}+b^{Iq}q^{**}\right)+b^{Iq}\left(2c^{q}q^{**}+c^{Iq}I^{**}\right)-c^{Iq}\left(b^{q}+b^{Iq}I^{**}\right)\\ +\frac{\left(2c^{q}q^{**}+c^{Iq}I^{**}\right)\left(b^{I}+b^{Iq}q^{**}\right)\left(b^{q}+b^{Iq}I^{**}\right)}{t}\\ +\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^{I}+c^{Iq}q^{**}\right)\right)\frac{\left(b^{q}+b^{Iq}I^{**}\right)^{2}}{t}\end{array}\right)\\ &\quad +\left(2c^{q}q^{**}+c^{Iq}I^{**}\right)\left(\begin{array}{c} 3b^{Iq}c^{q}-c^{Iq}\frac{\left(b^{q}+b^{Iq}I^{**}\right)^{2}}{t}\\ +\left(b^{q}+b^{Iq}I^{**}\right)\frac{2c^{q}\left(b^{I}+2b^{Iq}q^{**}\right)+c^{Iq}b^{Iq}I^{**}}{t}\end{array}\right).\end{aligned} \tag{A45}$$

Finally,

$$V_{qT_{1}}=0, V_{IT_{1}}=1, \tag{A46}$$

$$V_{qp_{0}}=\frac{b^{q}+b^{Iq}I^{**}}{2t}>0, \tag{A47}$$

$$V_{Ip_0} = \frac{1}{2t}\left[b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right] \gtrless 0, \tag{A48}$$

$$V_{qp_1} = I^{**}\left(\frac{b^q + b^{Iq}I^{**}}{2t}\right) > 0 \tag{A49}$$

and

$$V_{Ip_1} = \frac{1}{2t}\left[\begin{array}{c} I^{**}\left(b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j(I^{**})}{\partial I_i}\right) + t \\ -\frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right)^3}{4t^2\Delta}\left(\frac{2c^q q^{**} + c^{Iq}I^{**}}{2\left(b^q + b^{Iq}I^{**}\right)} - \alpha\right) \end{array}\right]. \tag{A50}$$

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