Article:
Ghandour, Ziad, Siciliani, Luigi and Straume, Odd Rune (2022) Investment and Quality Competition in Healthcare Markets. Journal of Health Economics. 102588. ISSN: 0167-6296

https://doi.org/10.1016/j.jhealeco.2022.102588

Investment and Quality Competition in Healthcare Markets*

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7 January 2022

Abstract

We study the strategic relationship between hospital investment and provision of service quality. We use a spatial competition framework and allow investment and quality to be complements or substitutes in patient benefit and provider cost. We assume that each hospital commits to a certain investment before deciding on service quality, and that investment is observable and contractible while quality is observable but not contractible. We show that, under a fixed DRG-pricing system, providers' lack of ability to commit to quality leads to under- or overinvestment, relative to the first-best solution. Underinvestment arises when the price-cost margin is positive, and quality and investments are strategic complements, which has implications for optimal contracting. Differently from the simultaneous-move case, the regulator must complement the payment with one more instrument to address under/overinvestment. We also analyse the welfare effects of different policy options (separate payment for investment, higher per-treatment prices, or DRG-refinement policies).

Keywords: Investment; Quality competition; Hospital payment.

JEL Classification: D24, I11, I18, L13

*We thank two anonymous referees for very helpful comments. This paper is financed by National Funds of the FCT –Portuguese Foundation for Science and Technology within the project UID/ECO/03182/2019. Ziad Ghandour acknowledges the FCT's PhD Studentship SFRH/BD/144210/2019.

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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. Throughout the analysis, we assume that investments are observable and contractible. For example, it would be relatively straightforward for a health regulator or purchaser to verify if a hospital has bought Magnetic Resonance Imaging machines, CT scans or has acquired other expensive technologies. In contrast, we assume that service quality for the health care provided to the patients is observable to patients but it is not contractible by the regulator. Service quality can encompass both clinical and non-clinical dimensions of quality. Clinical dimensions of quality include how successful the treatment was in recovering patient's health (for example reduction in pain and mobility for elective care) and, for more urgent care such as cancer, patient survival and quality of life for years after the treatment or the surgery. Non-clinical dimensions of quality include whether the patient was treated with respect, whether she was involved in decisions, and overall patient satisfaction. Providers can establish a good reputation for systematically providing high service quality, and this will contribute to higher levels of demand for such providers, while patients will try to avoid providers with poor service quality. For regulators it is much more difficult to contract service dimensions of quality, either clinical or non-clinical ones, as service quality is multi-dimensional and difficult to capture through a limited set of metrics. Although policymakers have been introducing pay-for-performance schemes that reward higher quality, these initiatives are still developing in scope, relate to only a minority of treatments provided by hospitals and so far have had limited or no effect on health outcomes (Milstein and Schreyoegg, 2016; Mendelson et al., 2017). In this study, we will therefore assume that service quality is observable but not verifiable and therefore not contractible. It would be incredibly costly for the regulator to specify in a contract what service quality should be provided by a hospital for each individual treatment and under each circumstance.[1]

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 transfer, where each of the policy instruments

[1] Health regulators typically have auditing mechanisms, which can take the form of (random or scheduled) inspections. However, these can be labour intensive and costly for the funder, and are therefore carried out infrequently. Moreover, these auditing mechanisms generally enforce minimum quality standards with penalties being triggered when these minimum standards are violated. Only a minority of providers will fall below such standards. Our analysis aims at analysing incentives for the vast majority of hospitals who compete for patients based on quality and therefore provide quality above those minimum standards (see Kuhn and Siciliani, 2013, for a theoretical analysis of auditing mechanisms for hospitals).

might depend on the level of investment. As a benchmark for comparison, we start out by deriving the socially optimal (first-best) solution. We then proceed by considering two different versions of the game played by the hospitals. First, we assume that investment and quality choices are made simultaneously. Subsequently we consider 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. For each of these two versions of the game, we study the welfare properties of the Nash equilibrium and characterise the payment contracts needed to implement the first-best solution. As discussed above, 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.

If investment and quality are chosen simultaneously, we show that the first-best solution can be implemented by a very simple payment contract, consisting only of a fixed DRG tariff. However, this is generally not the case if these decisions are made sequentially, since the price that induces the first-best quality level will lead to either under- or overinvestment. The reason for this distortion of investment incentives is that each hospital has an incentive to invest strategically in order to affect the intensity of quality competition at the subsequent stage of the game.

We find that the *direction* of this distortion 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*, hospitals underinvest (overinvest) if own investment and the quality of the competing hospital are strategic substitutes (complements). 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.

Whether providers work at a positive or negative price-cost margin is likely to depend on the health system. Systems with fewer beds per capita and higher capacity constraints are more likely to work at 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). Therefore, both positive and negative price-cost margins are plausible depending on the institutional arrangements. We also show that quality and investment tend to be strategic complements for those investments that reduce treatment costs, which is likely to apply to several new technologies, such as less invasive laparoscopic surgical treatments that also generates complementarities in health benefits and further reinforce the strategic complementarity.

Thus, in the case of sequential investment and quality decisions, the regulator must complement the payment contract with at least one more instrument to correctly incentivise investments, either through a transfer payment or a treatment price which depends on investment. In line with the previous analysis of the direction of the investment distortion, we show that the regulator should incentivise investment when investment and quality are strategic complements and the provider works at a positive price cost-margin, or disincentivise investments if the provider works at a negative price cost margin.[2]

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

[2] The results are reversed if quality and investment are strategic substitutes, which is more likely to arise if investment increases, rather than reduces, treatment costs. In this case, the regulator should disincentivise investment if the price-cost margin is positive, and incentivise investment if the price-cost margin is negative.

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 define social welfare and derive the first-best solution. In Section 5 we characterise the optimal payment contract when decisions on investments and service quality are made simultaneously. In Section 6, we consider the more realistic scenario of sequential decision making where hospitals first decide on investment and then on service quality. We analyse the welfare properties of the subgame-perfect Nash equilibrium and derive the optimal payment contract. In Section 7 we take a more positive approach by investigating the welfare effects of different realistic policy reforms to incentivise hospital investments. Finally, some concluding remarks and a further discussion of policy implications are offered in Section 8.

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 typically assumes that quality is observable but not verifiable, and it 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.[3] We advance the literature by further distinguishing between dimensions of quality that are not verifiable (despite being observable) and those that are verifiable and therefore contractible.[4]

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 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.[5] 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

[3] 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 (2021) 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.

[4] Kuhn and Siciliani (2013) assume that quality is verifiable only after an audit, but audits are costly and imperfect, meaning that they are not always informative. Accounting systems could potentially be used to infer efforts towards quality, but costs can be inflated or padded (Laffont and Tirole, 1993, chapter 12), and reflect a range of other factors (such as efficiency, and other unobservable determinants of costs, casemix and demand).

[5] 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.

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

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

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 ($b^{Iq} > 0$).[6] Another example when service quality and investment are complements 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. In other instances, perhaps less frequently, service quality and investment can be substitutes ($b^{Iq} < 0$). Robotic systems for minimally invasive surgery offer many advantages over traditional laparoscopic and open procedures. However, this technology allows for limited degrees of freedom and require multiple incisions, resulting in more pain for the patient leading to smaller marginal benefit of service quality (Dolph et al., 2019).[7]

We assume that both service quality and investment in new technologies are observable to the patient. For example, in terms of service quality, the patient can observe the diagnostic effort made by the doctor, the time spent with the patient, whether the patient is involved in decisions and treated with dignity, and ultimately if her health need is addressed. In relation to investment, the patient can observe whether the diagnostic tools are obsolete or modern, and whether the latest technologies are offered by the provider (non-invasive laparoscopic surgery, imaging scans, laser treatment, and robotics). Given that service quality and investment affect patient utility and health benefits, they will both play a role in determining the demand for each hospital. Analytically, each patient in the market makes a utility-maximising choice of hospital. Suppose 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 $D_j(I_i, I_j, q_i, q_j) = 1 - D_i(I_i, I_j, q_i, q_j)$. Therefore, hospitals with higher service quality and investment will have a higher demand. Policymakers

[6] The review by Buntin et al. (2011) found that most studies on introduction of electronic medical records and health information technology generated positive outcomes.

[7] Alemzadeh et al. (2016) find that da Vinci Surgical System and other robotic surgical systems have a non-negligible number of technical difficulties and complications associated with the use, such as electrical arcing of instruments, unintended operation of instruments, and system errors, which in turn impacted patients in terms of injuries or procedure interruptions. Hur et al. (2020) find negative impacts on patients when Balloon Sinulplasty was used, with complications ranging from catheter or balloon malfunction to imprecise navigation.

increasingly make use of quality indicators in the public domain to facilitate patient choice of provider (Siciliani et al., 2017). Such policies aim at making the demand more responsive to quality, which in our model is equivalent to a reduction in transportation costs. Such quality indicators however have limitations as they only capture some specific aspect of patient's experience and cover only a limited set of health conditions or treatments.[8] Note however that patients can still be informed about hospital quality and investment through word of mouth and hospital reputation (Moscone et al., 2012). The empirical literature on patient choice of hospital generally suggests that hospital demand does respond to quality, though the elasticity of demand to quality is low (Brekke et al., 2014; Gutacker et al., 2016).

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 therefore assume that while investments generate both variable and fixed costs, service quality that relates to diagnostic effort exercised by the doctor, the time spent with the patient, and staff friendliness is specific to each patient, and therefore does not involve a fixed cost component.

We assume that marginal treatment costs are given by[9]

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

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

[8] In some cases, quality indicators can also be used as part of pay-for-performance schemes, therefore making quality, at least to some extent, contractible. But these schemes suffer from similar limitations. They only apply to a limited set of treatments and conditions, and only a small share of hospital revenues are allocated through such incentive schemes. In the rest of the study, we therefore assume that service quality is not contractible.

[9] Although separable and linear-quadratic, the specification of patient benefit and variable cost are rather general as these allow for possible complementarity or substitution in quality and investment (and the marginal variable cost has to be increasing in quality to ensure the problem is well behaved). With a more general benefit and cost function, the results would be qualitatively very similar. However, in the sequential decision model the separable functional forms allow to obtain relatively simple expressions for the comparative statics of qualities with respect to investment (in stage 2), which are critical to characterise the equilibrium investment and quality in stage 1.

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 than 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.[10]

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 activity-indepedent 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 or not. In the latter case, the most realistic case is arguably that the transfer is increasing in investment, $\partial T/\partial I_i > 0$, where part or all of the cost of new investments are reimbursed by the funder. However, we also allow for the possibility that the regulator might use the transfer to disincentivise investments (i.e., $\partial T/\partial I_i < 0$).[11]

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

[10]For a given level of investment, we do not impose an upper limit on service quality. However, we assume that the marginal cost of service quality is increasing. Therefore, in our model we can always ensure that this upper limit is not hit by choosing a cost parameter c^q which is sufficiently high. In other words, we assume that there is always scope for the provider to improve service quality, but such improvements will be minimal in equilibrium if it is too costly for the provider to do so.

[11]In principle, the transfer can be either positive ($T > 0$) or negative ($T < 0$). However, this is irrelevant for effect of the transfer on investment incentives, which instead depend on the sign and magnitude of $\partial T/\partial I_i$.

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.[12] 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, $T\left(I_i\right)$,[13] 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

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

In line with the existing literature (e.g., Ellis and McGuire, 1986; Chalkley and Malcomson, 1998; Brekke et al., 2011) 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. This assumption is analytically similar to the literature on motivated agents in the public sector (Francois, 2000; Besley and Ghatak, 2005; Makris, 2009), where α can be interpreted as public service motivation. In the context of the health sector, it seems more intuitive to interpret α as altruistic concerns on the side of the doctors. Becoming a physician requires several years of demanding training on how to cure patients, and medical schools in many countries require their graduating students to take a modernised version of the Hippocratic oath.[14]

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

[13] Dranove et al. (2015) show that a hospital subsidy to promote the adoption of Electronic Medical Records accelerated its adoption by 10 percentage points between 2008 and 2011.

[14] Within our model, we can also more loosely reinterpret the parameter α as the degree of profit constraints of

4 Social welfare and the first-best solution

In this section we define social welfare and derive the socially optimal (first-best) solution. We apply a standard definition of social welfare, denoted by W, as the difference between aggregate patient utility and providers' costs, given by

$$W(I_i, I_j, q_i, q_j) = \varpi - \sum_{i=1}^{2} C(D_i, I_i, q_i). \tag{8}$$

where

$$\varpi = \int_0^{D_i(I_i,I_j,q_i,q_j)} (B(I_i, q_i) - tx)\, dx + \int_{D_i(I_i,I_j,q_i,q_j)}^{1} (B(I_j, q_j) - t\,(1-x))\, dx. \tag{9}$$

is aggregate patient utility.

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

$$W(I, q) = B(I, q) - \frac{t}{4} - c(I, q) - 2k(I). \tag{10}$$

Maximising (10) with respect to service quality and investment, we obtain the first best solution, denoted by (q^s, I^s), and implicitly given by[15]

$$\frac{\partial W(I,q)}{\partial q} = b^q + b^{Iq} I^s - \left(2c^q q^s + c^{Iq} I^s\right) = 0, \tag{11}$$

$$\frac{\partial W(I,q)}{\partial I} = b^I + b^{Iq} q^s - \left(c^I + c^{Iq} q^s\right) - 2\frac{\partial k(I^s)}{\partial I} = 0. \tag{12}$$

The socially optimal levels of investment and quality are characterised by the standard condition that marginal benefits equal marginal costs.

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a hospital. For example, public hospitals may have tighter constraints and more limited ability to use any residual financial surplus. Analytically, suppose that the hospital objective function is $V_i(I_i, I_j, q_i, q_j) = \alpha B(I_i, q_i) + (1 - \delta)\pi_i(I_i, I_j, q_i, q_j)$, where $0 \leq \delta < 1$. For $\delta = 0$, the hospital is for profit. For $\delta > 0$, the hospital gives a weight to profits which is less than one. Analytically, an increase in δ is equivalent to an increase in α, as we can rescale the payoff function as $\frac{\alpha}{(1-\delta)} B(I_i, q_i) + \pi_i(I_i, I_j, q_i, q_j)$ while the optimal quality and investment remain the same (see Brekke et al., 2012, for more details).

[15] Second order conditions are provided in Appendix A1.

In the subsequent sections of our analysis we derive the equilibrium investment and quality provision under two different game-theoretic assumptions regarding the sequence of decisions, where we distinguish between the cases of simultaneous and sequential choices of investment and service quality. For each of these cases, we show what type of payment scheme that is needed in order to implement the above-derived first-best solution.

5 Simultaneous choices of investment and quality

Suppose that both hospitals choose investment in technology and service quality simultaneously. The Nash equilibrium is implicitly characterised by the first-order conditions for hospital choice of q_i and I_i given by

$$\frac{\partial V_i(I_i, I_j, q_i, q_j)}{\partial q_i} = \left(b^q + b^{Iq} I_i\right) \left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] - \left(2c^q q_i + c^{Iq} I_i\right) D_i(I_i, I_j, q_i, q_j) = 0, \quad (13)$$

$$\begin{aligned} \frac{\partial V_i(I_i, I_j, q_i, q_j)}{\partial I_i} &= \left(b^I + b^{Iq} q_i\right) \left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] + \frac{\partial T(I_i)}{\partial I_i} \\ &\quad + \left[\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right] D_i(I_i, I_j, q_i, q_j) - \frac{\partial k(I_i)}{\partial I_i} = 0 \,. \end{aligned} \quad (14)$$

The second-order conditions are provided in Appendix A2. The optimal level of service quality is set such that the marginal benefit from the altruistic health gain and the marginal revenue are traded-off against the higher costs from higher demand and higher per-patient treatment costs. The optimal level of investment is analogous. The marginal benefits from investment include the altruistic health gain and the marginal revenue from higher demand, and potentially also a higher price and higher transfer. Investment is optimally provided when the sum of these marginal benefits is equal to marginal treatment costs from higher demand and the marginal investment cost (higher fixed costs), given by the final term in (14). 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[16]

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

$$V_q(I^*, q^*) = \left(\alpha + \frac{p(I^*) - c(I^*, q^*)}{2t}\right)\left(b^q + b^{Iq} I^*\right) - \frac{\left(2c^q q^* + c^{Iq} I^*\right)}{2} = 0, \tag{15}$$

$$\begin{aligned} V_I(I^*, q^*) \quad &= \quad \left(\alpha + \frac{p(I^*) - c(I^*, q^*)}{2t}\right)\left(b^I + b^{Iq} q^*\right) + \frac{\partial T(I^*)}{\partial I} \\ &\quad + \frac{1}{2}\left(\frac{\partial p(I^*)}{\partial I} - \left(c^I + c^{Iq} q^*\right)\right) - \frac{\partial k(I^*)}{\partial I} = 0 \; . \end{aligned} \tag{16}$$

Under which type of payment scheme will the Nash equilibrium outcome under simultaneous investment and quality choices coincide with the first-best solution? A straightforward comparison of (15)-(16) and (11)-(12), allows us to reach the following conclusion:

Proposition 1 *If investment and quality decisions are made simultaneously, the first-best solution can be implemented by setting*

$$\widehat{p} = c\left(I^s, q^s\right) + (1 - 2\alpha)t, \tag{17}$$

where I^s and q^s are defined by (11)-(12).

This 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 (17), 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 (17), 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.

6 Sequential choices of investment and quality

As a contrast to the case of simultaneous decision making, we now make the arguably more realistic assumption that hospitals make their investment decisions before the service 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.

The analysis in this section is done in three stages. We start out by deriving the subgame-perfect Nash equilibrium for a given payment scheme. Then we characterise the welfare properties of this equilibrium under the fixed-price payment scheme that yields first-best investments and quality provision under simultaneous decision making, and show that the first-best solution is generally not attainable with a simple payment rule of this kind. Finally, we derive the more sophisticated payment contract that implements the first-best outcome under sequential choices of investment and quality.

6.1 Equilibrium investment and quality for a given payment scheme

We derive the subgame-perfect Nash equilibrium by employing backwards induction, starting at the second stage of the game in which each hospital chooses its optimal provision of service quality.

6.1.1 Quality choices

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 (13), 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 A3.1), yielding

$$\frac{\partial q_i (I_i, I_j)}{\partial I_i} = \frac{1}{\Delta} \left(\begin{array}{c} -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t} \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j \right) \\ + \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j \right) \left[\begin{array}{c} \left(b^{Iq} \frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq} \right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right) \right) \frac{b^q + b^{Iq} I_i}{2t} \end{array} \right] \end{array} \right) \quad (18)$$

and

$$\frac{\partial q_j (I_i, I_j)}{\partial I_i} = \frac{1}{\Delta} \left(\begin{array}{c} \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t} \left(\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{2t} + c^q D_i \right) \\ + \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t} \left[\begin{array}{c} \left(b^{Iq} \frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq} \right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right) \right) \frac{b^q + b^{Iq} I_i}{2t} \end{array} \right] \end{array} \right), \quad (19)$$

where $\Delta > 0$ is given by (A18) in Appendix A3.1. The sign of (18) 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 (19) 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 (18)-(19), reduce to

$$\frac{\partial q_i}{\partial I_i} = -\frac{q_i b^I \left(q_j b^q + 2tD_j\right)}{3\left(b^q\right)^2 q_j q_i + 4t\left(D_j q_i b^q + D_i q_j b^q + tD_i D_j\right)} < 0 \tag{20}$$

and

$$\frac{\partial q_j}{\partial I_i} = \frac{q_j b^I \left(q_i b^q + tD_i\right)}{3\left(b^q\right)^2 q_j q_i + 4t\left(D_j q_i b^q + D_i q_j b^q + tD_i D_j\right)} > 0. \tag{21}$$

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 (13). 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 A3.1). 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.

6.1.2 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

$$\begin{aligned}\frac{\partial V_i(I_i,I_j,q_i,q_j)}{\partial I_i} &= \left(b^I+b^{Iq}q_i\right)\left[\alpha+\frac{p(I_i)-c(I_i,q_i)}{2t}\right]+\left(\frac{\partial p(I_i)}{\partial I_i}-\left(c^I+c^{Iq}q_i\right)\right)D_i \\ &+\frac{\partial T(I_i)}{\partial I_i}-\frac{\partial k(I_i)}{\partial I_i}-\frac{b^q+b^{Iq}I_j}{2t}\left[p(I_i)-c(I_i,q_i)\right]\frac{dq_j}{dI_i} \\ &+\left[\left(b^q+b^{Iq}I_i\right)\left[\alpha+\frac{p(I_i)-c(I_i,q_i)}{2t}\right]-\left(2c^q q_i+c^{Iq}I_i\right)D_i\right]\frac{dq_i}{dI_i}=0.\end{aligned} \tag{22}$$

The second order condition is provided in Appendix A3.2. The first line and the first two terms in the second line in (22) are identical to the investment condition in the simultaneous-move version of the game given by (14). The two additional terms in the second and third line of (22) capture the strategic effects of Hospital i's investment on the quality choices of both hospitals. However, the third line in (22) 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 (13)).

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

$$V_q(I^{**},q^{**})=\left(\alpha+\frac{p(I^{**})-c(I^{**},q^{**})}{2t}\right)\left(b^q+b^{Iq}I^{**}\right)-\frac{2c^q q^{**}+c^{Iq}I^{**}}{2}=0, \tag{23}$$

and

$$\begin{aligned}V_I(I^{**},q^{**}) &= \left(\alpha+\frac{p(I^{**})-c(I^{**},q^{**})}{2t}\right)\left(b^I+b^{Iq}q^{**}\right)+\frac{\partial T(I^{**})}{\partial I} \\ &+\frac{1}{2}\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^I+c^{Iq}q^{**}\right)\right)-\frac{\partial k(I^{**})}{\partial I} \\ &-\frac{\left(b^q+b^{Iq}I^{**}\right)}{2t}\left[p(I^{**})-c(I^{**},q^{**})\right]\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}=0\end{aligned} \tag{24}$$

where

$$\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}=\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{4t\Delta}\begin{pmatrix} c^q\left(b^I+b^{Iq}q^{**}\right) \\ +\left(b^q+b^{Iq}I^{**}\right)\begin{pmatrix} b^{Iq}\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{\left(b^q+b^{Iq}I^{**}\right)}-c^{Iq} \\ +\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)\left(b^I+b^{Iq}q^{**}\right)}{t} \\ +\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^I+c^{Iq}q^{**}\right)\right)\frac{b^q+b^{Iq}I^{**}}{t} \end{pmatrix}\end{pmatrix}. \tag{25}$$

6.2 Welfare properties under a fixed-price payment rule

We know from Proposition 1 that the first-best solution can be implemented under simultaneous decision making by a simple payment rule that just specifies a fixed price per treatment. Can a similar rule ensure first-best investments and quality also under sequential decision making? Comparing (15) and (23), we see that equilibrium quality is identical in both version of the game if and only if $I^*=I^{**}$. On the other hand, equilibrium investment is generally different when $q^*=q^{**}$. Comparing (16) and (24), the difference in the investment conditions is given by the last term in (24), which captures the strategic effect of own investment on the competing hospital's quality choice in the second stage. It follows that the fixed price level p which induces first-best quality will induce an investment level that differs from the first-best level. Conversely, the price level which induces first-best investments will lead to equilibrium quality that is not at the first-best level. In other words, under sequential decision making, the first-best outcome cannot be implemented by a simple pricing rule of the type specified in Proposition 1.

Suppose that the regulator nevertheless practices a simple payment rule in the form of a fixed per-treatment price. More specifically, suppose that the price is set at $\widehat{p}$, given by (17). We know that this price level induces the first-best solution if $I^{**}=I^*$ and $q^{**}=q^*$. However, since this is generally not the case under sequential decision making, what are the welfare properties of the subgame perfect Nash equilibrium under such a payment rule?

Let us first consider the hospitals' investment incentives. Whether a price level $\widehat{p}$ induces the hospitals to invest above or below the first-best level depends on the sign of the last line in (24). Thus, 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 on the sign of the price-cost margin, $\widehat{p}-c(I^{**},q^{**})$, which can be positive or negative depending on the degree of altruism.[17] Suppose that the price cost margin is positive in equilibrium, which requires that the hospitals are sufficiently profit-oriented. In this case 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 following proposition summarises the welfare properties of the hospitals' investment incentives:

Proposition 2 *Suppose that investment and quality choices are made sequentially and that the payment scheme is given by $\widehat{p}$ defined in (17). In this case, (i) if the equilibrium price-cost margin is positive, the hospitals invest below (above) the first-best level if own investment and rival's quality are strategic complements (substitutes), and (ii) if the equilibrium price-cost margin is negative, the hospitals invest below (above) the first-best level if own investment and rival's quality are strategic substitutes (complements).*

Since equilibrium investments generally differ from the first-best level for $p = \widehat{p}$, a corresponding deviation from the first-best solution also applies to the equilibrium provision of service quality. Whether the hospitals over- or under-provide quality depends in part on whether investment and quality are equilibrium complements or substitutes. This depends in turn on the sign of $\partial V_q / \partial I$, which is derived from (23). Evaluated at $\widehat{p}$, this is given by

$$\frac{\partial V_q(I^{**}, q^{**})}{\partial I} = -\frac{\left(b^q + b^{Iq} I^{**}\right)\left(c^I + c^{Iq} q^{**}\right)}{2t} + b^{Iq} \left(\frac{2c^q q^{**} + c^{Iq} I^{**}}{2\left(b^q + b^{Iq} I^{**}\right)} \right) - \frac{c^{Iq}}{2}. \tag{26}$$

The sign of (26) is generally ambiguous and depends on the signs of b^{Iq}, c^{Iq} and c^I. The welfare properties of the hospitals' incentives for quality provision are summarised as follows:

Proposition 3 *Suppose that investment and quality choices are made sequentially and that the payment scheme is given by a fixed treatment price set at the level which induces the first-best*

[17] To see that this is the case, we can re-write the equilibrium condition in (23) as

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

solution under simultaneous decision making. In this case, (i) if there is underinvestment (cf. Proposition 2), hospitals provide service quality below (above) the first-best level if investment and quality are equilibrium complements (substitutes), and (ii) if there is overinvestment (cf. Proposition 2), hospitals provide service quality below (above) the first-best level if investment and quality are equilibrium substitutes (complements).

While Propositions 2 and 3 provide general conditions, we can perhaps better illustrate the different possible cases by considering a specific example. Suppose that investment and quality are independent in health benefits and costs: $b^{Iq} = c^{Iq} = 0$. In this case, (26) reduces to

$$\frac{\partial V_q(I^{**}, q^{**})}{\partial I} = -\frac{b^q c^I}{2t}, \tag{27}$$

which implies that the sign of $\partial V_q(I^{**}, q^{**})/\partial I$ is uniquely determined by the sign of c^I. More specifically, investment and quality are equilibrium complements (substitutes) if higher investment reduces (increases) marginal treatment costs. Furthermore, (25) reduces to

$$\frac{\partial q_j\left(I^{**}\right)}{\partial I_i} = \frac{2c^q q^{**}}{4t\Delta}\left(c^q b^I + \frac{b^q}{t}\left(2c^q q^{**} b^I - c^I b^q\right)\right), \tag{28}$$

which implies that own investment and rival's quality are strategic complements if c^I is either negative or not too large in magnitude. Let us assume that the magnitude of $c^I \gtrless 0$ is such that $\partial q_j\left(I^{**}\right)/\partial I_i > 0$. Finally, let us define a threshold level of altruism, given by

$$\widehat{\alpha} := \frac{2c^q q^{**} + c^{Iq} I^{**}}{2\left(b^q + b^{Iq} I^{**}\right)}, \tag{29}$$

such that the equilibrium price-cost margin is positive (negative) if $\alpha < (>)\, \widehat{\alpha}$.[18] This example allows us to define four different cases.

Case 1 $\alpha < \widehat{\alpha}$ *and* $c^I < 0$.

If hospitals are sufficiently profit-oriented, so that the equilibrium price-cost margin is positive, each hospital has an incentive to underinvest in order to induce lower quality provision at the rival hospital. However, since both hospitals have the same unilateral incentive to use the investment

[18] The threshold value $\widehat{\alpha}$ is derived by solving the equilibrium condition (23) for the price-cost margin and evaluating its sign.

decision to strategically affect quality provision, these incentives cancel each other in the symmetric equilibrium. Nevertheless, if lower investments increase marginal treatment costs ($c^I < 0$), this will reduce equilibrium quality provision. Case 1 is thus characterised by both *underinvestment and underprovision of quality.*

Case 2 $\alpha > \widehat{\alpha}$ *and* $c^I < 0$.

If the hospitals are sufficiently altruistic, so that the equilibrium price-cost margin is negative, each hospital has an a unilateral 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. However, if higher investments reduce marginal treatment costs ($c^I < 0$), this will increase equilibrium quality provision. Case 2 is thus characterised by both *overinvestment and overprovision of quality.*

Case 3 $\alpha < \widehat{\alpha}$ *and* $c^I > 0$.

If the degree of hospital altruism is sufficiently low to yield underinvestment, but lower investment reduces marginal treatment costs ($c^I > 0$), this will lead to an increase in equilibrium quality provision. Case 3 is thus characterised by *underinvestment but overprovision of quality.*

Case 4 $\alpha > \widehat{\alpha}$ *and* $c^I > 0$.

Finally, if the hospitals are sufficiently altruistic to overinvest, but higher investment increases marginal treatment costs ($c^I > 0$), this will lead to a reduction in equilibrium quality provision. Case 4 is thus characterised by *overinvestment but underprovision of quality.*

6.3 The optimal payment scheme

As we have shown in the previous subsection, a simple payment scheme with just a fixed per-treatment price is not sufficient to implement the first-best solution when investment and quality are chosen sequentially (in a game-theoretic sense). The next proposition characterises the class of optimal payment schemes in this case:

Proposition 4 *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*

$$\widetilde{p}(I^{**}) = c(I^{**}, q^{**}) + (1-2\alpha)t = c(I^s, q^s) + (1-2\alpha)t, \tag{30}$$

and

$$2\frac{\partial \widetilde{T}\left(I^{**}\right)}{\partial I_i}+\frac{\partial \widetilde{p}\left(I^{**}\right)}{\partial I_i}=(1-2\alpha)\left(b^q+b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}, \tag{31}$$

with (I^{**}, q^{**}) *implicitly given by (23)-(24) and* $\partial q_j\left(I^{**}\right)/\partial I_i$ *given by (25).*

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. Compared with simple payment rule given in Proposition 1, the optimal payment contract under sequential decision making must therefore be complemented by at least one more instrument which incentivises investments separately. This can be done by making either the transfer payment or the per-treatment price dependent on investment; i.e., $\partial T/\partial I_i \neq 0$ or $\partial p/\partial I_i \neq 0$.[19]

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 transfer 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 transfer are linear in investment, i.e., $p\left(I_i\right)=p_0+p_1 I_i$ and $T\left(I_i\right)=T_0+T_1 I_i$. The first-best solution can then be implemented in two different ways:

(i) A simple optimal payment rule is such that $\widehat{p}_0=\widetilde{p}_0=c\left(I^s, q^s\right)+(1-2\alpha)t$ 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 $\widetilde{T}_1=(1/2-\alpha)\left(b^q+b^{Iq}I^s\right)\left(\partial q_j\left(I^s\right)/\partial I_i\right)$ in the sequential game. This payment involves only a fixed per-treatment price under both games, and a transfer which either increases or decreases in investment under the sequential game.

(ii) An alternative optimal payment is such that $\widehat{p}_0=c\left(I^s, q^s\right)+(1-2\alpha)t$ and $\widehat{p}_1=\widehat{T}_1=0$ under the simultaneous game, whereas $\widetilde{p}_0=c\left(I^s, q^s\right)+(1-2\alpha)t-\widetilde{p}_1 I^s$, $\widetilde{p}_1=(1-2\alpha)\left(b^q+b^{Iq}I^s\right)\left(\partial q_j\left(I^s\right)/\partial I_i\right)$ 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 $\widetilde{p}_1 \neq 0$ 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

[19] 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.

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 hospitals' incentive to underinvest, either through the transfer 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.

7 Policy options

We now 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 section 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.

In the following we investigate three different policy options, which reflect observed differences in real-world payment schemes. 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

$$W(I^{**}, q^{**}) = B(I^{**}, q^{**}) - \frac{t}{4} - c(I^{**}, q^{**}) - 2k(I^{**}). \tag{32}$$

7.1 Paying separately for investment

Consider a policy that introduces a payment rule which rewards investment in health technologies through the transfer 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 (32) with respect to T_1 yields

$$\frac{dW(I^{**},q^{**})}{dT_1} = \frac{\partial W(I^{**},q^{**})}{\partial I}\frac{\partial I^{**}}{\partial T_1} + \frac{\partial W(I^{**},q^{**})}{\partial q}\frac{\partial q^{**}}{\partial T_1}, \tag{33}$$

with

$$\frac{\partial I^{**}}{\partial T_1} = \frac{1}{\phi}\left[\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right)}{2t} + c^q\right] > 0, \tag{34}$$

$$\frac{\partial q^{**}}{\partial T_1} = \frac{V_{qI}}{\phi} \gtrless 0, \tag{35}$$

where the definitions of $\phi > 0$ and $V_{qI} \gtrless 0$, and further details, are given in Appendix A3.3.

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.

7.2 Paying for investment through a higher DRG price

Consider a policy which replaces a payment rule where investment is paid through a separate transfer 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 (32) with respect to p_0 yields

$$\frac{dW(I^{**}, q^{**})}{dp_0} = \frac{\partial W(I^{**}, q^{**})}{\partial I}\frac{\partial I^{**}}{\partial p_0} + \frac{\partial W(I^{**}, q^{**})}{\partial q}\frac{\partial q^{**}}{\partial p_0}, \tag{36}$$

with

$$\frac{\partial I^{**}}{\partial p_0} = \frac{1}{2t\phi}\left[\left(b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right)(-V_{qq}) + V_{Iq}\left(b^q + b^{Iq}I^{**}\right)\right], \tag{37}$$

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

and where the expressions for $V_{II} < 0$, $V_{qq} < 0$, $V_{qI} \gtrless 0$ and $V_{Iq} \gtrless 0$ are given in Appendix A3.3.

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 (38). 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 (37), 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.

7.3 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 (32) with respect to p_1 yields

$$\frac{dW(I^{**},q^{**})}{dp_1}=\frac{\partial W(I^{**},q^{**})}{\partial I}\frac{\partial I^{**}}{\partial p_1}+\frac{\partial W(I^{**},q^{**})}{\partial q}\frac{\partial q^{**}}{\partial p_1}, \tag{39}$$

with

$$\frac{\partial I^{**}}{\partial p_1}=\frac{1}{\phi}\left(V_{Ip_1}\left(-V_{qq}\right)+I^{**}\frac{V_{Iq}\left(b^q+b^{Iq}I^{**}\right)}{2t}\right), \tag{40}$$

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

$$V_{Ip_1}=I^{**}V_{Ip_0}+\frac{1}{2}-\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)\left(b^q+b^{Iq}I^{**}\right)^3}{8t^3\Delta}\left(p(I^{**})-c(I^{**},q^{**})\right)\gtrless 0, \tag{42}$$

$$V_{Ip_0}=\frac{1}{2t}\left[b^I+b^{Iq}q^{**}-\left(b^q+b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right]\gtrless 0, \tag{43}$$

where V_{Ip_i} is the effect of a marginal increase in p_i, $i=0,1$, 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 (38) is similar to the first term in (41)). The direct effects on *investment* incentives are also present under this policy, and captured by the first term in (42). 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 (42). 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 6.1.[20] 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 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

[20] It follows from (25) that

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

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.

8 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. Under the realistic assumption that investment and quality choices are made sequentially, we show that hospitals have an incentive to underinvest if (i) the price-cost margin is positive and own investment and the quality of the competing hospital are strategic complements and or (ii) the price-cost margin is negative and own investment and quality are strategic substitutes. 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 regulator has to incentivise investment when underinvestment arises, and disincentivise it under overinvestment. The analysis therefore highlights the role of two main factors. The first is whether providers work at a positive or negative price-cost margin. In the Introduction, we have discussed that whether the price-cost margin is positive or negative depends on the health system, and in particular whether the price is set at the average cost, or at a lower level (as in Norway or in England under blended payments). A second key factor is whether investment and quality are strategic complements or substitutes. We have shown that in the absence of complementarity or substitutability in benefits and costs, investment and quality are strategic complements, and this strategic complementarity is further reinforced in the presence of complementarities on benefits or costs, which seems plausible for several technologies. This suggests that in countries using full activity-based funding, underinvestment is likely to arise, and it may be welfare improving to incentivise investment through additional payment that reward investment.

In terms of policy implications, our analysis also 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.

In terms of possible empirical analyses, future work could 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). Finally, empirical work could investigate whether higher investments increase or reduce treatment costs of service quality, as this assumption has implication for the degree of complementarity and substitutability of investment and quality within providers.

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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 6-7, respectively.

A1. Second-order conditions for the first-best solution

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

$$\frac{\partial^2 W}{\partial q_i^2} = -2c^q < 0, \tag{A1}$$

$$\frac{\partial^2 W}{\partial I_i^2} = -2\frac{\partial^2 k(I_i)}{\partial I_i^2} < 0 \tag{A2}$$

and

$$\frac{\partial^2 W}{\partial q_i^2}\frac{\partial^2 W}{\partial I_i^2} - \left(\frac{\partial^2 W}{\partial q \partial I}\right)^2 = 4c^q \frac{\partial^2 k(I_i)}{\partial I_i^2} - \left(b^{Iq} - c^{Iq}\right)^2 > 0. \tag{A3}$$

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

A2. Second-order conditions in the simultaneous-move game

The second-order conditions for the optimal investment and quality choices by Hospital i are given by

$$\frac{\partial^2 V_i(q_i, q_j, I_i, I_j)}{\partial q_i^2} = -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} - 2c^q D_i < 0, \tag{A4}$$

$$\frac{\partial^2 V_i(q_i, q_j, I_i, I_j)}{\partial I_i^2} = \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^I + b^{Iq} q_i}{t} + \frac{\partial^2 p(I_i)}{\partial I_i^2} D_i + \frac{\partial^2 T(I_i)}{\partial T_i^2} - \frac{\partial^2 k(I_i)}{\partial I_i^2} < 0, \tag{A5}$$

and

$$\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_i}{\partial I_i^2} - \left(\frac{\partial^2 V_i}{\partial I_i \partial q_i}\right)^2 \geq 0, \tag{A6}$$

where $\partial^2 V_i / \partial I_i \partial q_i$ is given by (A16) below. These conditions are satisfied if $k(I_i)$ is sufficiently convex.

A3. Supplementary calculations for the sequential-move game

A3.1 Derivation of (18) and (19) in Section 6.1.1

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

$$\left(b^q + b^{Iq} I_i\right)\left[\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right] - \left(2c^q q_i + c^{Iq} I_i\right) D_i(I_i, I_j, q_i, q_j) = 0, \tag{A7}$$

$$\left(b^q + b^{Iq} I_j\right)\left[\alpha + \frac{p(I_j) - c(I_j, q_j)}{2t}\right] - \left(2c^q q_j + c^{Iq} I_j\right) D_j(I_i, I_j, q_i, q_j) = 0. \tag{A8}$$

Totally differentiating these conditions with respect to I_i, we obtain

$$\begin{bmatrix} \frac{\partial^2 V_i}{\partial q_i^2} & \frac{\partial^2 V_i}{\partial q_i \partial q_j} \\ \frac{\partial^2 V_j}{\partial q_j \partial q_i} & \frac{\partial^2 V_j}{\partial q_j^2} \end{bmatrix}\begin{bmatrix} dq_i \\ dq_j \end{bmatrix} + \begin{bmatrix} \frac{\partial^2 V_i}{\partial q_i \partial I_i} \\ \frac{\partial^2 V_j}{\partial q_j \partial I_i} \end{bmatrix} dI_i = 0, \tag{A9}$$

which gives

$$\frac{dq_i}{dI_i} = \frac{-\frac{\partial^2 V_i}{\partial q_i \partial I_i}\frac{\partial^2 V_j}{\partial q_j^2} + \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial I_i}}{\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j^2} - \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial q_i}}, \tag{A10}$$

$$\frac{dq_j}{dI_i} = \frac{-\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j \partial I_i} + \frac{\partial^2 V_j}{\partial q_j \partial q_i}\frac{\partial^2 V_i}{\partial q_i \partial I_i}}{\frac{\partial^2 V_i}{\partial q_i^2}\frac{\partial^2 V_j}{\partial q_j^2} - \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial q_i}}, \tag{A11}$$

where

$$\frac{\partial^2 V_i}{\partial q_i^2} = -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)}{t} - 2c^q D_i < 0. \tag{A12}$$

$$\frac{\partial^2 V_j}{\partial q_j^2} = -\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} - 2c^q D_j < 0, \tag{A13}$$

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

$$\frac{\partial^2 V_j}{\partial q_j \partial q_i} = \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_i\right)}{2t} > 0, \tag{A15}$$

$$\begin{aligned} \frac{\partial^2 V_i}{\partial q_i \partial I_i} &= b^{Iq}\left(\alpha + \frac{p(I_i) - c(I_i, q_i)}{2t}\right) + \left(\frac{\partial p}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \\ &\quad - \left(2c^q q_i + c^{Iq} I_i\right)\frac{b^I + b^{Iq} q_i}{2t} - c^{Iq} D_i, \end{aligned} \tag{A16}$$

$$\frac{\partial^2 V_j}{\partial q_j \partial I_i} = \frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^I + b^{Iq} q_i\right)}{2t} > 0. \tag{A17}$$

Denote by Δ the denominator in (A10) and (A11), which, after some manipulations, can be expressed as

$$\Delta = \frac{1}{4t^2}\left(\begin{array}{c} 3\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right)\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right) \\ +8tc^q\left(\begin{array}{c} D_j\left(2c^q q_i + c^{Iq} I_i\right)\left(b^q + b^{Iq} I_i\right) \\ +D_i\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right) + 2tc^q D_i D_j \end{array}\right) \end{array}\right) \tag{A18}$$

Using the first-order condition optimal quality, (13), the numerator in (A10) can be written as

$$\begin{aligned} & -\frac{\partial^2 V_i}{\partial q_i \partial I_i}\frac{\partial^2 V_j}{\partial q_j^2} + \frac{\partial^2 V_i}{\partial q_i \partial q_j}\frac{\partial^2 V_j}{\partial q_j \partial I_i} \\ = & \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \\ & -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j\right). \end{aligned} \tag{A19}$$

Therefore, by substitution, (18) is given by

$$\frac{dq_i}{dI_i} = \frac{1}{\Delta}\left(\begin{array}{c} \left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{t} + 2c^q D_j\right)\left[\begin{array}{c} \left(b^{Iq}\frac{\left(2c^q q_i + c^{Iq} I_i\right)}{\left(b^q + b^{Iq} I_i\right)} - c^{Iq}\right) D_i \\ + \left(\frac{\partial p(I_i)}{\partial I_i} - \left(c^I + c^{Iq} q_i\right)\right)\frac{b^q + b^{Iq} I_i}{2t} \end{array}\right] \\ -\frac{\left(2c^q q_i + c^{Iq} I_i\right)\left(b^I + b^{Iq} q_i\right)}{t}\left(\frac{\left(2c^q q_j + c^{Iq} I_j\right)\left(b^q + b^{Iq} I_j\right)}{4t} + c^q D_j\right) \end{array}\right), \tag{A20}$$

Similarly, by using the first-order condition for optimal quality, (13) and rearranging some terms, the numerator in (A11) is given by

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

Therefore, (19) is given by

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

A3.2 Second order conditions

In the investment game, the second order condition for Hospital i 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 (19) with respect to I_i. Define ψ as the numerator in (19). In this case $\Upsilon = \left(\psi_{I_i}\Delta - \psi\Delta_{I_i}\right)/\Delta^2$, where

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

and

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

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

A3.3 Comparative statics

Considering the subgame-perfect Nash Equilibrium implicitly defined by (23)-(24), the comparative statics results reported in Section 7 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:

$$
\frac{\partial q^{**}}{\partial T_1} = \frac{-V_{qT_1} V_{II} + V_{qI} V_{IT_1}}{V_{qq} V_{II} - V_{Iq} V_{qI}}, \tag{A26}
$$

$$
\frac{\partial I^{**}}{\partial T_1} = \frac{-V_{qq} V_{IT_1} + V_{qT_1} V_{Iq}}{V_{qq} V_{II} - V_{Iq} V_{qI}}, \tag{A27}
$$

$$
\frac{\partial q^{**}}{\partial p_0} = \frac{-V_{qp_0} V_{II} + V_{qI} V_{Ip_0}}{\phi}, \tag{A28}
$$

$$
\frac{\partial I^{**}}{\partial p_0} = \frac{-V_{qq} V_{Ip_0} + V_{qp_0} V_{Iq}}{\phi}, \tag{A29}
$$

$$
\frac{\partial q^{**}}{\partial p_1} = \frac{-V_{qp_1} V_{II} + V_{qI} V_{Ip_1}}{\phi}, \tag{A30}
$$

$$
\frac{\partial I^{**}}{\partial p_1} = \frac{-V_{qq} V_{Ip_1} + V_{qp_1} V_{Iq}}{\phi}, \tag{A31}
$$

where $\phi := V_{qq} V_{II} - V_{Iq} V_{qI} > 0$. The different terms in the numerators of (A26)-(A31) are defined as follows:

$$
V_{qq} = -\frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^q + b^{Iq} I^{**}\right)}{2t} - c^q < 0 \tag{A32}
$$

and

$$
\begin{aligned}
V_{II} &= \frac{\left(b^I + b^{Iq} q^{**}\right)}{2t} \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right) \right) - \frac{\partial^2 k(I^{**})}{\partial I^2} \\
&\quad - \Psi \frac{\left(b^q + b^{Iq} I^{**}\right)}{2t} \left[p(I^{**}) - c(I^{**}, q^{**}) \right] \\
&\quad - \frac{1}{2t} \left[\begin{array}{c} b^{Iq} \left(p(I^{**}) - c(I^{**}, q^{**}) \right) + \\ \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right) \right) \left(b^q + b^{Iq} I^{**}\right) \end{array} \right] \frac{\partial q_j \left(I^{**}\right)}{\partial I_i} < 0 \, ,
\end{aligned} \tag{A33}
$$

where Ψ is the derivative of (25) with respect to I. Defining Ξ as the numerator in (25), 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

$$
\Delta_I = \frac{\left[c^{Iq} b^q + 2b^{Iq} \left(c^q q^{**} + c^{Iq} I^{**}\right)\right] \left[3 \left(2c^q q^{**} + c^{Iq} I^{**}\right) \left(b^q + b^{Iq} I^{**}\right) + 4tc^q\right]}{2t^2}, \tag{A34}
$$

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

$$
\begin{aligned}
\Xi_I &= c^{Iq} \left(\begin{array}{c} c^q \left(b^I + b^{Iq} q^{**}\right) + b^{Iq} \left(2c^q q^{**} + c^{Iq} I^{**}\right) - c^{Iq} \left(b^q + b^{Iq} I^{**}\right) \\ + \frac{\left(2c^q q^{**} + c^{Iq} I^{**}\right)\left(b^I + b^{Iq} q^{**}\right)\left(b^q + b^{Iq} I^{**}\right)}{t} \\ + \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right) \right) \frac{\left(b^q + b^{Iq} I^{**}\right)^2}{t} \end{array} \right) \\
&\quad + \left(2c^q q^{**} + c^{Iq} I^{**}\right) \left(\begin{array}{c} \left(c^{Iq} b^q + 2b^{Iq} \left(c^q q^{**} + c^{Iq} I^{**}\right)\right) \frac{\left(b^I + b^{Iq} q^{**}\right)}{t} \\ + \frac{\partial^2 p(I^{**})}{\partial I^2} \frac{\left(b^q + b^{Iq} I^{**}\right)^2}{t} \\ + 2b^{Iq} \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right) \right) \frac{\left(b^q + b^{Iq} I^{**}\right)}{t} \end{array} \right) .
\end{aligned} \tag{A35}
$$

Further:

$$
V_{qI} = b^{Iq} \left(\frac{2c^q q^{**} + c^{Iq} I^{**}}{2 \left(b^q + b^{Iq} I^{**}\right)} \right) + \frac{b^q + b^{Iq} I^{**}}{2t} \left(\frac{\partial p(I^{**})}{\partial I} - \left(c^I + c^{Iq} q^{**}\right) \right) - \frac{c^{Iq}}{2} \lesseqgtr 0 \tag{A36}
$$

and

$$V_{Iq} = b^{Iq}\left(\frac{2c^q q^{**}+c^{Iq}I^{**}}{2\left(b^q+b^{Iq}I^{**}\right)}\right)+\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)}{2t}\left(\left(b^q+b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}-\left(b^I+b^{Iq}q^{**}\right)\right)$$
$$-\frac{c^{Iq}}{2}-\Phi\frac{\left(b^q+b^{Iq}I^{**}\right)}{2t}\left(p(I^{**})-c(I^{**},q^{**})\right)\lesseqgtr 0, \tag{A37}$$

where Φ is the derivative of (25) 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 (25) with respect to q is given by

$$\Delta_q = \frac{c^q\left(b^q+b^{Iq}I^{**}\right)\left[3\left(2c^q q^{**}+c^{Iq}I^{**}\right)\left(b^q+b^{Iq}I^{**}\right)+4tc^q\right]}{t^2}, \tag{A38}$$

and the derivative of the numerator Ξ in (25) with respect to q, is given by

$$\Xi_q = 2c^q\begin{pmatrix} c^q\left(b^I+b^{Iq}q^{**}\right)+b^{Iq}\left(2c^q q^{**}+c^{Iq}I^{**}\right)-c^{Iq}\left(b^q+b^{Iq}I^{**}\right) \\ +\frac{\left(2c^q q^{**}+c^{Iq}I^{**}\right)\left(b^I+b^{Iq}q^{**}\right)\left(b^q+b^{Iq}I^{**}\right)}{t} \\ +\left(\frac{\partial p(I^{**})}{\partial I}-\left(c^I+c^{Iq}q^{**}\right)\right)\frac{\left(b^q+b^{Iq}I^{**}\right)^2}{t}\end{pmatrix}$$
$$+\left(2c^q q^{**}+c^{Iq}I^{**}\right)\begin{pmatrix} 3b^{Iq}c^q - c^{Iq}\frac{\left(b^q+b^{Iq}I^{**}\right)^2}{t} \\ +\left(b^q+b^{Iq}I^{**}\right)\frac{2c^q\left(b^I+2b^{Iq}q^{**}\right)+c^{Iq}b^{Iq}I^{**}}{t}\end{pmatrix}. \tag{A39}$$

Finally,

$$V_{qT_1} = 0, V_{IT_1} = 1, \tag{A40}$$

$$V_{qp_0} = \frac{b^q+b^{Iq}I^{**}}{2t} > 0, \tag{A41}$$

$$V_{Ip_0} = \frac{1}{2t}\left[b^I+b^{Iq}q^{**}-\left(b^q+b^{Iq}I^{**}\right)\frac{\partial q_j\left(I^{**}\right)}{\partial I_i}\right] \gtreqless 0, \tag{A42}$$

$$V_{qp_1} = I^{**}\left(\frac{b^q+b^{Iq}I^{**}}{2t}\right) > 0 \tag{A43}$$

and

$$V_{Ip_1} = \frac{1}{2t}\left[\begin{array}{c} I^{**}\left(b^I + b^{Iq}q^{**} - \left(b^q + b^{Iq}I^{**}\right)\frac{\partial q_j(I^{**})}{\partial I_i}\right) + t \\ -\frac{\left(2c^q q^{**} + c^{Iq}I^{**}\right)\left(b^q + b^{Iq}I^{**}\right)^3}{4t^2\Delta}\left(\frac{2c^q q^{**} + c^{Iq}I^{**}}{2(b^q + b^{Iq}I^{**})} - \alpha\right)\end{array}\right]. \tag{A45}$$