Heterogeneous effects of incentive contracts in healthcare

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Abstract

The paper analyzes heterogeneous hospital behavior in response to various designs of incentive scheme with reward function for measured quality. We develop a theoretical model with intertemporal optimization and compare the effect of three reward functions with stimulus: 1) linked to achievement, i.e. the value of quality in a given year, 2) associated with the improvement in quality from period to period, or 3) proportionate to maximum of hospital's achievement and improvement of quality. Additionally, we allow for threshold-based extensions of the schemes, where stimulus is capped - no reward is received by hospitals which do not meet the quality target. The designs correspond to applications of quality incentive programs in healthcare systems of different countries. Specifically, quality improvement was introduced in the reward function of Medicare's pilot program and was then used in the UK, France, Korea and New Zealand, as well as in the US nationwide incentive program "value-based purchasing".

The analytical predictions of the theoretical model and the numerical solutions show that the response to each incentive varies for hospitals with low, median and high quality. The effect of incentive measured as increase of hospital quality is proportionate to baseline quality for reward functions linked to achievement or improvement. As for achievement with caps or for the maximum of achievement and improvement, the strongest effect of each incentive is observed at hospitals with median quality. High-quality hospitals increase their quality under each incentive, but not as fast as the median types. The mean quality goes down in all hospital groups under reward based on improvement with cap.

An extension of the model considers fixed cost of hospital's investment into quality improvement. The hospitals split into two groups, and the effect of incentive on quality increase is larger in the group that chooses to bear the fixed cost.

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1 Introduction

Public contracting with firms in conditions of asymmetric information about their technology presents an agency problem where the government, acting as the principal, can use price regulation to induce a socially efficient level of cost reduction (Laffont and Tirole, 1993; Shleifer, 1985). But reduction of firm costs entails risks for product quality (Chalkley and Malcomson, 1998a; Ellis and McGuire, 1996; Hölmstrom and Milgrom, 1991). One way of addressing this problem is a mechanism of extrinsic motivation, which uses quality indicators to define the performance level of each firm and relates remuneration to performance. Performance may be defined in terms of *achievement* – i.e. the value of quality in a given period t or in terms of *improvement* – the change in quality from period t to period $t+1$. Pay-for-performance mechanism is widely employed in the public sector (in civil service, education and social work) and is particularly valuable in healthcare, since healthcare is the classic example of an industry with asymmetric information where sustained quality of service is extremely important.

Ideally, pay-for-performance should create incentives for each healthcare provider, shifting the whole distribution of quality (Cashin, 2014c). However, the most widely used scheme – threshold-based incentives, which reward achievement as performance above a certain target value of a quality indicator – fails to provide sufficient stimuli for agents who are far below the threshold (Mullen et al., 2010; Siciliani, 2009). A more promising incentive mechanism makes the reward proportional to the measured quality and takes quality improvement into consideration. An example is Medicare's value-based purchasing, implemented at national level in the US in 2013 on the basis of a reward function that increases in linear fashion and relates the aggregate measure of hospital quality to remuneration. The aggregate measure is a weighted average of scores for several quality measures, and the score for each measure is computed as the maximum of hospital's achievement and improvement points.

Bonuses proportional to quality achievement or quality improvement, but provided only to agents with performance above a certain threshold level of quality (e.g. as in Medicare's pilot program, and its variants used in the UK and Korea), represent partial implementation of the continuous reward function (Rosenthal, 2014; Cashin, 2014c).

The introduction of a quality incentive with a continuous reward function is based on the plausible expectation that such a mechanism will be effective in stimulating healthcare providers with any initial level of quality. However, the degree of quality improvement may be different for different quality groups. The existing theoretical literature on incentive contracts in healthcare, as well as the empirical research on heterogeneous effect with respect to quality groups, tends to focus on threshold-based schemes based on achievement (Mullen et al., 2010; Siciliani, 2009; Doran et al., 2008) or improvement (Ryan et al., 2012b; Werner et al., 2011). To the best of our knowledge, research on the continuous reward function has been limited to investigation of the mean effect of per-patient bonuses in primary care (Kristensen et al., 2016). We discovered only one empirical paper on heterogeneous impact of per-patient bonuses (Coleman et al., 2007) but the inverse relationship between quality improvement and prior levels of quality, which it discovers, may not be regarded as the effect of the quality incentives, since the relationship holds for both incentivized and non-incentivized physicians.

The purpose of this paper is to analyze heterogeneity in response to a pay-for-performance mechanism in healthcare with different variants of the continuous and threshold-based reward functions. We start by building a theoretical model of hospital behavior, the key features of which may be summarized as follows. First, a hospital's objective function includes an altruistic component which is proportionate to the quality of provided services. This assumption is supported by abundant evidence about the intrinsic motivation of healthcare providers and accounts for the fact that some hospitals pay more attention to quality than others. Second, the model differentiates between unobserved quality and its measurable proxy, since the incentive payment is a function of observed quality that increases in linear fashion. Third, there are dynamic aspects induced by the behavior of the regulator and the hospital. The behavior of the regulator adds a dynamic to the hospital's task since the incentive payment lags performance: it is computed according to quality measured in the previous period.

Additional dynamics arise from the hospital's intertemporal incentive when the quality payments are expected to continue over a long term: the hospital understands that its current policies towards quality of care will influence future reimbursement. Empirical support for the existence of this intertemporal incentive is provided by interviews with hospital executives about the impact of per-patient bonuses in primary care (Bokhour et al., 2006; Conrad et al., 2006) and the effect of the linear rule in Medicare's value-based purchasing on the behavior of hospital executives and physicians (Smith, 2017; Jones, 2014). Hospital officials explicitly state that pay-for-performance impacts the way their hospital "is going to be paid in future" (Jones, 2014, p. 120), that "the stakes were high" and that each year their hospital could risk a large sum of money in case of poor performance (Smith, 2017, p. 145). Accordingly, the hospital executives "appear capable of creating an internal environment of high energy and high expectations" (Conrad et al., 2006, p. 449).

The theoretical model considers two types of a continuous reward function: based on achievement or improvement. The model forecasts that the impact of the continuous quality incentive is proportionate to baseline level of quality. The result holds both for the schemes linked to achievement and improvement, and the magnitude of the effect is larger for the former mechanism. Theoretical predictions of the model on heterogeneity of the effect are supported by the results of the numerical solution of the model. Another theoretical prediction of the model which is verified numerically is positive relationship between the effect of pay-for-performance and the strength of the quality incentives, measured in terms of the share of hospital funds that are "at risk" in the scheme. The numerical solutions are also provided for general forms of the reward functions with stimulus based on: 1) achievement with caps, 2) improvement with cap, 3) maximum of achievement and improvement. We discover that all variants of the reward function have a negligible effect for raising quality of low-quality hospitals. The incentive scheme associated with the maximum of achievement and improvement outperforms the incentive based on achievement at the group of high-quality hospitals. Yet, incorporation of improvement into the reward function has adverse effects for median quality hospitals: they may temporarily decrease their quality in order to raise it in the subsequent period and get an award for improvement.

The results correspond to the findings of the health policy literature about stronger emphasis on quality-improving activities at high-quality hospitals or among high-quality physicians in comparison with low-quality hospitals and physicians (Damberg et al., 2009; Vina et al., 2009; Grossbart, 2006). Specific measures for quality improvement may include establishing best practices for each condition and dissemination of these practices at professional conferences, using clinical pathways and clinical guidelines, and providing feedback to physicians by reporting internal data (for instance, by letting the name of a successful heart surgeon or surgery group be known (Damberg et al., 2014, 2010, 2009; Vina et al., 2009; Bentley and Nash, 1998)).

The predictions of our theoretical model and the results of the numerical solution of the model may reconcile the contradictory findings in the empirical literature about the effect of incentives across groups of hospitals with varying quality. Moreover, our results suggest that the stylized fact of the inverse relationship between quality increase owing to the incentives scheme and the baseline quality is incorrect and should be reconsidered. Indeed, we discover that the effect of incentive measured as increase of hospital quality is proportionate to baseline quality for reward functions based on achievement or improvement. As for achievement with caps or for the maximum of achievement and improvement, the strongest effect of each incentive is observed at hospitals with median quality. High-quality hospitals increase their quality under each incentive, but not as fast as the median types. The mean quality goes down in all hospital groups under improvement with cap.

The remainder of the paper is structured as follows. Section 2 reviews the design of quality incentives in healthcare. A theoretical model of quality incentive based on achievement and improvement, and the predictions of heterogeneous effect for quality groups of hospitals are given in Section 3. Section 4 describes the procedure for the numerical solution of the model and gives the results for various types of the reward functions. Section 5 dwells on extensions of the model and implications of the model's predictions. A discussion of channels used for quality improvement and of the search for the size of quality incentive is provided in Section 6. Proofs and further extensions in terms of robustness to functional form assumptions are given in the Appendix.

2 Pay-for-performance in healthcare

2.1 Background

The origins of incentive regulation in conditions of asymmetric information can be traced to the approach used by Baron and Myerson (1982) and the yardstick competition model by Shleifer (1985), which establishes the price for each firm depending on costs of comparable firms. Applied to healthcare, yardstick competition requires the identification of a hospital's products and determination of a reasonable cost for each product. This is done by assigning patients to a limited number of medically justified diagnosis-related groups (DRGs), with a statistically stable distribution of resource consumption within each group (Thompson et al., 1979). This assignment is the core of a prospective payment system, which is a reimbursement method that provides fixed payments for a patient with a given DRG. Piloted in New Jersey in the 1980s and then applied to all Medicare hospitals in the United States, prospective payment has now been adopted in most healthcare systems around the world.

Prospective payment aims to make product and service provision more efficient, but it may adversely affect the quality of product if quality and output are interrelated objectives of the firm (Hölmstrom and Milgrom, 1991). In this regard, Ma (1994) and Ma and Mak (2015) show that prospective payment can lead to efficient levels of costs and quality when these are the only two objectives of a hospital and when quality is verifiable. If quality is observable but non-verifiable, prospective payment causes underprovision of quality when quality and quantity are net substitutes (Laffont and Tirole, 1993). Actual implementation of prospective payment systems in various countries has indeed been accompanied by deterioration of healthcare quality measured, for instance, as intensity of care, mortality or readmission (Eggleston and Hsieh, 2004; Ellis and McGuire, 1996).

Theoretical approaches to designing a contract for an efficient level of costs and quality often assume that the social planner observes the true quality or at least knows the response of patient demand or hospital costs to quality (Ma and Mak, 2015; Chalkley and Malcomson, 1998b; Ma, 1994). Some papers do acknowledge the unobservable character of healthcare quality, and attempts have been made to use patient demand as a proxy for quality when designing an incentive contract (Chalkley and Malcomson, 1998b).

Practical implementation of an incentive contract for quality uses a number of verifiable performance measures as proxies for the unobserved quality of healthcare. The mechanism is called pay-for-performance and dates from the early 1980s when various performance targets were used for enhancing the quality of natural monopolies and telecommunications provision (Kridel et al., 1996; Joskow and Schmalensee, 1986).

Numerous programs for monitoring the value of various quality indicators were launched in healthcare in the US and Europe in the 1980s and 1990s (Christianson et al., 2008; Wagner et al., 2006), including one of the first examples of nationwide implementation of pay-for-performance for family practices in the UK in 2004 (Campbell et al., 2009). Pay-for-performance is currently used in hospitals in Brazil, Korea, the Netherlands, the UK and the US (Cashin et al., 2014; Dückers et al., 2009), in Germany's sickness funds (de Bruin et al., 2011; Busse, 2004) and in primary care in Australia, Canada, Estonia, France, New Zealand, Spain, Sweden, Turkey, the UK and the US (Practice Assist, 2017; Cashin et al., 2014; Li et al., 2014; Ödesjö et al., 2015; Buetow, 2008; Gené-Badia et al., 2007).

Pay-for-performance mechanisms in healthcare have several features in common. Firstly, the verifiable performance measures, which approximate true quality, cover several aspects of care: clinical quality (for instance, prescription of a certain drug or administration of a certain procedure), patient experience (subjective assessment of services that are received) and care outcomes (mortality or morbidity). Secondly, the incentive mechanisms aim to stimulate quality improvement. Several designs may be used for this purpose, and we classify them below as threshold-based with a flat bonus, threshold-based with a quality-related bonus, and continuously increasing reward function for quality. The theoretical model in this paper and the empirical analysis concerns the latter mechanism.

2.2 Design of quality incentive schemes

2.2.1 Reward function based on achievement

The most common variant of the scheme provides a flat bonus for achievement, i.e. for quality above a certain target value in a given period. The value (the threshold) can be set as an absolute standard or as a relative standard, related to the empirical distribution of agents' quality. Another type of the scheme considers several thresholds and uses a stepwise reward function. The flat bonus approach is the earliest quality-based reimbursement scheme and is used in primary care in the UK, Canada, Estonia and Spain. Thresholds are commonly established for clinical indicators, which describe the percentage of patients who have undergone immunization and screening, or who have good health outcomes (for example in terms of cholesterol level or blood pressure).

Theoretical analysis of threshold-based incentive schemes forecasts undesired effects for agents in the highest percentiles of quality, whose performance may deteriorate owing a crowding-out of motivation by extrinsic incentives (Bénabou and Tirole, 2006, 2003; Kreps, 1997), conformism (Murdock, 2002) or due to lessening of effort in tournaments with other healthcare providers (Casas-Arce and Martínez-Jerez, 2009; Prendergast, 1999; Radner, 1985).

Low quality agents who are very far from the threshold also lack incentives for improvement, since their cost of enhancing quality to the target value is less than the quality bonus (Mullen et al., 2010). Moreover, a threshold-based incentive scheme may cause various unintended effects, such as artificial enhancement of the quality indicator. An example of this would be artificial increase of the share of patients who undergo necessary procedures, achieved by underreporting the number of eligible patients (Gravelle et al., 2010).

A reward function with continuous bonus associated with hospital's achievement which is used in Maryland is another type of the scheme. Hospitals are grouped according to the value of their composite quality indicator relative to the mean for the state: hospitals above the mean receive a bonus proportional to their quality, while hospitals below the mean suffer a proportional loss (Murray, 2014).

2.2.2 Threshold-based with continuous bonus and consideration of quality improvement

This approach provides a continuous reward for performance above the threshold. Per-discharge awards for top performing hospitals, organized by Premier Inc. for the Hospital Quality Incentive Demonstration (HQID), offer an example of the approach. This voluntary program for

Medicare hospitals was implemented in 2003–2008 and can be regarded as a pilot for the subsequent nationwide introduction of value-based purchasing. The HQID program used quality measures of the clinical process of care for five health conditions: acute myocardial infarction, heart failure, pneumonia, coronary artery bypass grafting, and knee or hip replacement. Main features of the HQID incentive scheme have been described in the literature (Cashin, 2014c; Ryan et al., 2012b). They included a reputational incentive: reporting of hospitals, where quality was above the median level. Financial incentives in the first phase of the program (2003–2006) offered a bonus of, respectively, 2% and 1% of their Medicare revenue to hospitals in the top first and second decile of quality measures for each health condition.

The second phase of the program (2006–2008) incentivized achievement and improvement through three types of stimuli: 1) an attainment award for exceeding the median score that existed two years prior to the pilot, 2) a top-performance award for being in the top two quality deciles in the current year, 3) a top-improvement award for exceeding the median score in the current year and for being in the top two deciles for quality improvement. Although financial rewards to hospitals in the second stage were allocated on a per-patient basis, estimated values of the top-performance and top-improvement awards suggest that they were roughly comparable to a 1% bonus per condition, while the attainment award was equivalent to a 0.25% bonus over and above Medicare revenue per condition (Ryan et al., 2012a). Hospitals in the tenth and ninth deciles (the bottom deciles) for all quality measures by the end of the second phase of the program suffered a 2% and 1% reduction in Medicare payments, respectively.

The US pilot served as a model for the Advancing Quality hospital program in the UK and for hospital incentive programs in France, New Zealand and Korea (Kristensen et al., 2016; Bisiaux and Chi, 2014; Bousquet et al., 2014; Sutton et al., 2012; Buetow, 2008). For instance, in the UK hospitals could opt for three awards: 1) attainment for quality above the median value of the first year, 2) achievement for quality above the median value of the second year, 3) improvement for quality above the median value of the first year and for being in the top 25-percent of hospitals according to their quality increase (Kristensen et al., 2016). At the same time, the incentive scheme in Korea looks only at hospital's improvement: awards are given to 2 groups with the highest quality increase and penalties are applied to 2 groups with the lowest increase (Bisiaux and Chi, 2014). The mechanism in France uses the reward function which considers improvement points for hospitals below the threshold (computed as the median quality level across hospitals) but uses achievement points for hospitals above the threshold (Bousquet et al., 2014).

The success of the Medicare's pilot in terms of improving the mean level of composite measure of hospital quality (Ryan, 2009; Christianson et al., 2008; Lindenauer et al., 2007; Glickman et al., 2007; Grossbart, 2006) led to the nationwide implementation of the incentive scheme at the US Medicare hospitals.

2.2.3 Reward function associated with the maximum of scores for achievement and improvement

The mechanism has been applied to discharges in the inpatient prospective payment system at acute-care Medicare hospitals since 2013.[1] The scheme reduced Medicare's DRG-based payment to each hospital by a factor α which equaled 0.01 in 2013, was increased annually by 0.0025 in 2014–2017 and has remained flat at 0.02 since 2017. The accumulated saving is redistributed across hospitals according to the adjustment coefficient, which is computed as a linear function of the composite quality measure: $1 + \left(\kappa \frac{TPS_i}{100} - 1\right) \cdot \alpha$, where i is the index of a hospital and TPS_i is the hospital's *total performance score* ($0 \leq TPS_i \leq 100$). Hospitals are rewarded if the adjustment coefficient is above one and suffer financial loss otherwise. While the pilot program required additional financial resources, the nationwide quality incentives scheme is budget-neutral and the value of the slope κ is chosen to ensure budget neutrality.

The composite quality measure – *total performance score* is a weighted sum of scores for measures in several domains: timely implementation of recommended medical interventions (*clinical process* of care), quality of healthcare as perceived by patients (*patient experience* of care), survival rates for AMI, heart failure and pneumonia patients and other proxies for *outcome* of care, healthcare-associated infections and other measures of *safety* of care, and spending per beneficiary as a measure of *efficiency* of care.

The domain score is the sum of the scores for its measures, and measure scores are computed according to a discrete scale of 0 to 10. Higher score reflects higher position of the hospital in the empirical distribution of the quality measure in a given year or higher improvement of the quality measure relative to the baseline period.

Specifically, achievement points evaluate a hospital's performance relative to other hospitals in a given year, and improvement points are computed to assess change in the hospital's own performance in the given year relative to the baseline period. Then, for each measure, the highest of the two (achievement points or improvement points) is used as the hospital's score for that measure. (See details on domain scores in Appendix A).

3 Model

3.1 Setup

Under the principal-agent approach on the healthcare market, a principal (a government or a social planner) contracts agents (physicians or hospitals) on behalf of consumers (patients). Pay-for-performance incentive schemes, such as Medicare's value-based purchasing, target hospitals rather than physicians. However, in our model we equate incentives for the hospital with incentives for its physicians and consider the hospital as an aggregate agent. This approach matches changes in the management of Medicare hospitals, designed to bridge the potential

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[1] Two US states are exceptions to the rule: Puerto Rico, which only started innovating its healthcare system in 2015 and Maryland, which has a unique model for hospital financing.

gap between the interests of hospitals and of physicians (Centers for Medicare and Medicaid Services, 2007b).

Based on the results of numerous experimental and empirical studies,[2] we take account of the existence of altruism on the healthcare market. We assume that hospitals (physicians) have a type-specific altruism θ, where θ is a random variable with expected value $\bar{\theta}$. It should be noted that hospital-specific altruism becomes a source of hospital heterogeneity in our model. An alternative approach to modeling hospital heterogeneity, which leads to similar quantitative results, considers hospital-specific marginal costs as in Laffont and Tirole (1993).

We denote the quality of healthcare in period t as q_t. The quality depends on the hospital's efforts e_t, and we assume $q_t = e_t + \varepsilon_t$, where $\varepsilon_t \sim N(0, \sigma_\varepsilon^2)$ (Eggleston, 2005). We abstract from multi-dimensional efforts and multi-dimensional quality in our model. The linear relationship between efforts and quality is another simplification but we relax it in Appendix C, which contains a numerical solution of a more general model.

The hospital has an additively separable objective function consisting of three parts: the benefit B from altruistic behavior (i.e. from the expected change in the patient's health due to treatment), wealth (net profit) π, and disutility of quality-enhancing efforts $C(e_t)$ (Blomqvist, 1997; Eggleston, 2005; Oxholm et al., 2018):

$$U = B + \pi - C.$$

The benefit from altruism depends positively on quality and we let $B = \theta q_t$. The hospital's net profit π is the difference between revenue and the financial cost of providing services. Revenue is the demand for healthcare multiplied by the per-patient price. Demand depends positively on quality (Ma and Mak, 2015; Siciliani et al., 2013; Chalkley and Malcomson, 1998b; Ellis and McGuire, 1996; Ma, 1994) and we assume a linear form of demand aq_t, where $a > 0$.

The per-patient price is the sum of R_t (approximates reimbursement for outlier cases in the prospective payment system or may be regarded as part of a cost-sharing tariff) and prospective payment p_t, which is subject to quality adjustment.

Based on the design of most pay-for-performance schemes, we assume that the principal computes a measure of hospital's quality m_t as a function of q_{t-1}, q_{t-2} etc. $m_t = M(q_{t-1}, q_{t-2}, \dots)$. The value of m_t is used for assigning additional stimulus to the hospital. Note that the hospital does not know m_t at $t-1$. The initial value m_0 is assumed to be known.

We model a linear rule in Medicare's value-based purchasing, so the principal adjusts the hospital's prospective payment through multiplication of the unit price p_t by the quality-adjustment coefficient $1 - \alpha + \kappa m_t$. Here $0 < \alpha < 1$ is the share of the hospital's revenue, which goes to the nationally accumulated fund and is then redistributed according to a linear function with slope κ. The quality incentives scheme is budget-neutral, and both κ and α are exogenous to a hospital. The hospital's costs are proportional to the volume of healthcare services provided

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[2] See empirical literature on quantification of altruism (Li et al., 2014; Gruber and Owings, 1996) and various experimental works, such as Brosig-Koch et al. (2016).

with the coefficient $d_t > 0$, which may be taken as a proxy for the existing technology and is regarded as exogenous by the hospital.

The hospital's net profit is then $\pi = aq_t(R_t + p_t(1 - \alpha + \kappa m_t) - d_t)$.

The final part of the hospital's objective function is the disutility of efforts $C(e_t) = ce_t^2/2$, where $c > 0$.

Note that the marginal cost of quality improvement is zero at zero effort. In other words our main model assumes that all costs related to quality are variable. As an extension, we consider a version of the model where the fixed cost of quality improvement enters the hospital problem. Examples of such cost include the expense of several million USD to install an Electronic Health Records system that enables the hospital to collect and analyse data on patients and their diagnoses. In the extended model we assume that the fixed cost born in period one enables the hospital to maintain higher quality at lower variable cost in period 2. As a result, the hospitals split into two groups. A group with higher θ chooses to bear the fixed cost of quality improvements while the group of hospitals with lower θ decides to refuse the burden of the fixed cost.

The hospital's objective function is

$$U_t(m_t, q_t, e_t) = \theta q_t + aq_t(R_t + p_t(1 - \alpha + \kappa m_t) - d_t) - ce_t^2/2.$$

In period t the hospital chooses the level of efforts e_t, given the technology d_t, prices R_t, p_t and the quality-adjustment coefficient (all are set by the principal). Effort e_t determines the level of quality q_t, while q_t influences the estimated value of quality m_{t+1} and, hence, the value of the hospital's objective function in period $t + 1$. The discount factor for the utility of future periods is $\beta \in (0, 1)$.

The hospital's intertemporal maximization problem is:

$$\begin{gathered}\max_{\{e_t, q_t, m_t\}} E \sum_{t=0}^{\infty} \beta^t U_t(m_t, q_t, e_t) \\ \text{s.t.} \quad q_t = e_t + \varepsilon_t, \text{ where } \varepsilon_t \sim N(0, \sigma_\varepsilon^2) \text{ i.i.d.}, \; t = 0, 1, \dots, \\ m_t = M(q_{t-1}, q_{t-2}, \dots), \; t = 1, 2, \dots, \text{ and } q_{-1}, q_{-2}, \dots \text{are given.}\end{gathered} \tag{1}$$

Note that the model considers two types of incentives for quality improvement. One incentive stems from the fact that the hospital increases the demand for its services by raising quality. Another incentive is intertemporal and is associated with pay-for-performance: the hospital realizes that if quality goes up in the current period, the payoff from the regulator will be higher in the next period.

3.2 Assumptions

The analysis is based on assumptions about the redistributive character of the incentive scheme (Assumption 1), time-invariance of unit prices and costs of hospitals (Assumption 2) and sufficiently high disutility of quality-enhancing efforts (Assumption 3). Note that Assumption 1 may be relaxed, as is argued in the section below on extensions of the model. However, Assumptions 2 and 3 are necessary conditions for the existence of a stable solution and a stationary steady state for the hospital problem (1).

There are several essential features of the model which enable the closed-form solution. Firstly, the private utility of physician θq is linear in quality. Secondly, the quality-adjustment coefficient is linear in the measured quality (this corresponds to Medicare's incentive scheme). Finally, demand for hospital services is linear in quality and the marginal cost is linear in the quality-enhancing efforts. The model, in the general case with monotonically increasing physician utility, use of any convex cost function and any concave profit function cannot be solved analytically and requires a numerical solution. An example of a numerical solution of the model in this general case is given in Appendix C. It shows that the effect of pay-for-performance, albeit non-linear, still has all the implied properties discussed below: the reform effect is positive and increases monotonically in α and in θ.

Assumption 1. *The principal relates parameters κ and α through the condition*

$$E(\kappa m_t - \alpha) = 0.$$

This assumption means that the expected value of the adjustment coefficient equals one, which corresponds to budget neutrality of the quality incentive scheme.

Assumption 2. *Prices and unit costs are fixed, so $R_t \equiv R$, $p_t \equiv p$, $d_t \equiv d$.*

Assumption 3. *The disutility of effort is sufficiently high: $ap\kappa(1+\beta)^2 < c$.*

If Assumption 3 does not hold then the stationary steady state for the measured quality m_t either does not exist or is unstable. This means that if the power of the pay-for-performance scheme is too high relative to the hospital's costs, then the incentives of the best hospitals are too strong and the incentives of the worst hospitals are too weak, which leads to divergence in quality.

3.3 Solution of the model with linear reward function based on achievement

Firstly, we let $m_t = q_{t-1}$. This simplified framework corresponds to remuneration of hospital's achievement and enables to obtain an analytical solution of the model.[3]

3.3.1 Solution of the hospital problem

In this section we show that the solution of the hospital utility maximization problem under assumptions 2 and 3 converges to a stationary process and we find this process. The first proposition describes solution of the problem for a single hospital.[4]

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[3] The extension of the model which links incentive to the maximum of achievement and improvement is solved through the simulation approach.

[4] Proofs for all the statements can be found in Appendix B.

Proposition 1. *Under assumptions 2 and 3 the solution of the hospital utility maximization problem for a hospital of type* θ *is a linear function of* q_{t-1}*:*

$$e_t = \mu(\theta) + \phi_1(q_{t-1} - \mu(\theta)), \tag{2}$$

where

$$\mu(\theta) = \eta_0 + \eta_1\theta, \tag{3}$$

for

$$\eta_0 = \frac{a(R-d) + ap(1-\alpha)}{c - ap\kappa(1+\beta)}, \quad \eta_1 = \frac{1}{c - ap\kappa(1+\beta)}, \tag{4}$$

and

$$\phi_1 = \frac{2ap\kappa}{c + \sqrt{c^2 - 4\beta(ap\kappa)^2}}. \tag{5}$$

Next, since $q_t = e_t + \varepsilon_t$, the following corollary describes the process for quality:

Corollary 2. *The quality level* q_t *of a hospital with type* θ *forms a stable first order autoregressive process*

$$q_t = \mu(\theta) + \phi_1(q_{t-1} - \mu(\theta)) + \varepsilon_t, \tag{6}$$

where $\mu(\theta)$ *and* ϕ_1 *are defined by* (3) *and* (5) *respectively.*

The autoregressive process in Corollary 2 is stable, and this ensures existence and stability of the hospital's quality found as a solution to the hospital problem. The following corollary claims the existence of a stationary steady state for the hospital's quality.

Corollary 3. *Under the conditions of assumptions 2 and 3, the quality of a hospital with type* θ *converges to a stationary steady state process for which*

$$E(q_t \mid q_{t-1}, \theta) = \mu(\theta) + \phi_1(q_{t-1} - \mu(\theta)), \tag{7}$$

so the long-term expected value of q_t *conditional only on* θ *is*

$$E(q_t \mid \theta) = \mu(\theta) = \frac{a(R-d) + \theta + ap(1-\alpha)}{c - ap\kappa(1+\beta)}. \tag{8}$$

3.3.2 Stationary equilibrium

Next, consider the steady state level of quality for all hospitals and add the budget neutrality assumption 1. Taking expectation of (8) yields the long-term unconditional expected value of the quality for all hospitals.

Corollary 4. *The unconditional expected value of the quality equals*

$$\mu = E(q_t) = \frac{a(R-d) + \bar{\theta} + ap(1-\alpha)}{c - ap\kappa(1+\beta)}. \tag{9}$$

So Assumption 3 may be modified for a budget-neutral scheme, where κ is endogeneously determined by α:

Corollary 5. *The technical condition from Assumption 3 under the budget neutrality assumption 1 becomes:*

$$\alpha < \frac{a(R-d)+\bar{\theta}+ap}{ap(1+\beta+\beta^2)}, \tag{10}$$

which means that very high value of policy parameter α may break stability of the system.

Proposition 6 describes hospital response to pay-for-performance: the mean value of measured quality m_t and the parameter of convergence ϕ_1 increase in α.

Proposition 6. *Suppose that assumptions 1, 2, and 3 hold. Then the stationary steady state parameters are:*

$$\mu = \frac{a(R-d)+\bar{\theta}+ap(1+\beta\alpha)}{c}, \tag{11}$$

$$\eta_0 = \frac{(a(R-d)+\bar{\theta}+ap(1+\beta\alpha))(a(R-d)+ap(1-\alpha))}{c(a(R-d)+\bar{\theta}+ap(1-\alpha))}, \tag{12}$$

$$\eta_1 = \frac{a(R-d)+\bar{\theta}+ap(1+\beta\alpha)}{c(a(R-d)+\bar{\theta}+ap(1-\alpha))}, \tag{13}$$

$$\phi_1 = \frac{2ap\alpha}{a(R-d)+\bar{\theta}+ap(1+\beta\alpha)+\sqrt{(a(R-d)+\bar{\theta}+ap(1+\beta\alpha))^2-4\beta(ap\alpha)^2}}, \tag{14}$$

$0<\phi_1<1$ *and μ, η_1, ϕ_1 increase in α (η_0 can be an increasing or decreasing function of α, depending on $\bar{\theta}$).*

3.3.3 Effect of pay-for-performance

Putting together equations (3), (12) and (13), we obtain the corollary on the effect of pay-for-performance:

Corollary 7. *The long-term mean of the quality of a hospital of type θ equals*

$$E(q_t \mid \theta) = \frac{a(R-d)+\bar{\theta}+ap(1+\beta\alpha)}{c} \cdot \frac{a(R-d)+\theta+ap(1-\alpha)}{a(R-d)+\bar{\theta}+ap(1-\alpha)}. \tag{15}$$

The mean function (15) increases in θ and its second mixed derivative in θ and α is positive.

Corollary 7 shows that the effect of pay-for-performance increases with respect to the hospital-specific parameter θ.

3.4 Solution of the model with reward function based on difference measured quality

In this section we use another definition of the hospital performance: the difference between quality levels in the last two periods, so $m_t = M(q_{t-1}, q_{t-2}) = q_{t-1} - q_{t-2}$. It roughly corresponds to improvement in Medicare's pay-for-performance schemes, and allows to solve the model analytically.

3.4.1 Solution of the hospital problem

In this section we show that the solution of the hospital utility maximization problem under assumptions 2 and 3 converges to a stationary process and next, we find this process. The proposition below describes solution of the problem for a single hospital.

Proposition 8. *Under assumptions 2 and 3 the solution of the hospital utility maximization problem for a hospital of type* θ *is a linear function of* q_{t-1} *and* q_{t-2}*:*

$$e_t = \mu(\alpha,\kappa,\theta) + \phi_1(\kappa)(q_{t-1} - \mu(\alpha,\kappa,\theta)) + \phi_2(\kappa)(q_{t-2} - \mu(\alpha,\kappa,\theta)), \tag{16}$$

where $\mu(\alpha,\kappa,\theta)$ *is a decreasing function of* α*, an increasing function of* κ*,* θ *and is linear in* α *and* θ*.*

Next, since $q_t = e_t + \varepsilon_t$, the following corollary describes the process for quality:

Corollary 9. *The quality level* q_t *of a hospital with type* θ *forms a stable second order autoregressive process*

$$q_t = \mu(\alpha,\kappa,\theta) + \phi_1(\kappa)(q_{t-1} - \mu(\alpha,\kappa,\theta)) + \phi_2(\kappa)(q_{t-2} - \mu(\alpha,\kappa,\theta)) + \varepsilon_t. \tag{17}$$

This process has a characteristic equation with complex roots. They have the same absolute value which increases in κ*. We regard this value as the measure of persistence for the quality process.*

The autoregressive process in Corollary 9 is stable, and this ensures existence and stability of the solution, as well as the existence of a stationary steady state for the hospital's quality.

Corollary 10. *Under the conditions of assumptions 2 and 3, the quality of a hospital with type* θ *converges to a stationary steady state process for which*

$$E(q_t \mid q_{t-1}, q_{t-2}, \theta) = \mu(\alpha,\kappa,\theta) + \phi_1(\kappa)(q_{t-1} - \mu(\alpha,\kappa,\theta)) + \phi_2(\kappa)(q_{t-2} - \mu(\alpha,\kappa,\theta)), \tag{18}$$

so the long-term expected value of q_t *conditional only on* θ *is*

$$E(q_t \mid \theta) = \mu(\alpha,\kappa,\theta). \tag{19}$$

3.4.2 Stationary equilibrium

Next, consider the steady state level of quality for all hospitals and add the budget neutrality assumption 1. Note that $E(q_{t-1}) = E(q_{t-2})$, so taking expectation of (19) yields the long-term unconditional expected value of the quality for all hospitals and the condition for κ and α.

Corollary 11. *The unconditional expected value of the quality equals*

$$\mu = E(q_t) = E(\mu(\alpha, \kappa, \theta)) = \mu(\alpha, \kappa, \bar{\theta}). \tag{20}$$

The scheme is budget-neutral if and only if $\alpha = 0$.

Corollary 11 and Proposition 8 show that the effect of pay-for-performance increases with respect to the hospital-specific parameter θ.

4 Solution of the model with the general form of reward function

While the theoretical section provided analytical solution of the model for continuous incentive schemes, this section considers three more general forms of the reward function.

- Achievement with caps:

  $$m_t = M(q_{t-1}) = \begin{cases} 0 & \text{if } q_{t-1} \leq T, \\ \dfrac{q_{t-1} - T}{B - T} & \text{if } T < q_{t-1} < B, \\ 1 & \text{if } q_{t-1} \geq B, \end{cases}$$

  where T is a threshold, B is a benchmark, and $B > T$. This specification of the achievement is closer to the one employed in Medicare's value-based purchasing. The main difference is the fact that we model a continuous award while the stimulus in Medicare is stepwise with eleven discrete values (from 0 to 10).

- Improvement with caps:

  $$m_t = M(q_{t-1}, q_{t-2}) = \begin{cases} 0 & \text{if } q_{t-1} \leq q_{t-2}, \\ \dfrac{q_{t-1} - q_{t-2}}{K} & \text{if } q_{t-1} > q_{t-2}, \end{cases}$$

  for some constant $K > 0$. This specification resembles improvement in Medicare, and hospitals are not punished for deterioration of quality.

- Maximum of achievement and improvement (both are with caps):

  $$m_t = M(q_{t-1}, q_{t-2}) = \begin{cases} 1 & \text{if } q_{t-1} \geq B, \\ 0 & \text{if } q_{t-1} \leq T \text{ and } q_{t-1} \leq q_{t-2}, \\ \max\left\{ \dfrac{q_{t-1} - T}{B - T}, \dfrac{q_{t-1} - q_{t-2}}{B - q_{t-2}} \right\} & \text{otherwise,} \end{cases}$$

  where T is a threshold, B is a benchmark, and $B > T$. Here $(q_{t-1} - T)/(B - T)$, $(q_{t-1} - q_{t-2})/(B - q_{t-2})$ represent achievement and improvement respectively. With the exception of being continuous, this specification is the most accurate formulation of Medicare's incentive.

Since the specifications are piecewise linear, the model can not be solved analytically. So a numerical solution to the model is provided for each of the three incentives. For comparison with the effect of the two continuous reward functions which were considered in the theoretical section, the numerical solutions are also provided for these two functions.

- Achievement:
$$m_t = M(q_{t-1}) = \frac{q_{t-1} - T}{B - T},$$
where T is a threshold, B is a benchmark, and $B > T$. Hospitals are stimulated for quality above the threshold and punished for quality below the threshold.

- Improvement:
$$m_t = M(q_{t-1}, q_{t-2}) = \frac{q_{t-1} - q_{t-2}}{K},$$
for some constant $K > 0$. Hospitals receive a stimulus for quality improvement and suffer a loss in case of quality deterioration.

For each of these five incentive schemes, the numerical solution of the model is found through the algorithm below.

- Set the values for the parameters which enter the hospital problem: $T = 30$, $B = 70$, $K = 50$, $a = 2$, $R = 2$, $d = 1$, $p = 1$, $c = 0.3$, $\beta = 0.5$, $\sigma = 10$, $\alpha = 0$.

- Establish the ranges for the parameter of altruism $\theta \in [0, 15]$ and for the quality incentive $\kappa \in [0, 2.5]$. These values and ranges of the parameters ensure heterogeneous behavior of hospitals with different θ and κ: baseline quality is close to benchmark B for hospitals with high θ while baseline quality lines in the proximity to threshold T for hospitals with low θ.

- Using the grid for the ranges of θ and κ, numerically solve the utility maximization problem (1). The solution is the optimal level of efforts e^* which is a function of q_{t-1} in the schemes with reward for achievement. If improvement is included in the reward function, e^* becomes a function of (q_{t-2}, q_{t-1}).

- Simulate the evolution of quality in each hospital as $q_t = e^*(q_{t-1}) + \varepsilon_t$ (or $q_t = e^*(q_{t-1}, q_{t-1}) + \varepsilon_t$) and compute the mean value of quality.

- Compute the persistence parameter as the correlation coefficient between q_{t-1} and q_t for the simulated time series of quality.

4.1 Achievement and achievement with caps

Figures 1–3 show the effect of the incentive parameter κ on hospitals with different θ for the two variants of the reward function based on achievement: the scheme with compensation proportionate to achievement (the grey surface) and the scheme which has caps – the maximal and the minimal awards are respectively fixed for hospitals below the threshold and above the benchmark value of quality (the blue surface). As may be inferred from Figure 1, both schemes lead to increase of the mean quality, and the mean quality improvement is larger in case of achievement without any caps. Figure 1 also shows that for a fixed value of κ, the mean quality grows nonlinearly in θ. Specifically, the most and the least altruistic hospitals exhibit slower growth of quality, which can be attributed to the fact that they primarily belong to the range of quality where the stimulus is capped. Figure 3 demonstrates that persistence parameter λ becomes close to zero for hospitals with the highest and the lowest θ under rewards based on achievement with caps. Yet, λ does not differ across hospitals with different values of θ when incentive is associated with achievement.

Figure 2 shows plane sections of Figure 1 for low, median and high values of θ. The reform intensity κ has a negligible impact of mean quality of hospitals with low θ under the reward based on achievement with caps. But quality decreases in κ at hospitals with low θ under the incentive based achievement. Indeed, in the latter case the quality is likely to be below the threshold T, so hospitals are punished for low achievement. As for hospitals with median and high θ, the increase of their mean quality in κ is smaller in case of achievement with caps.

The effect of incentive scheme measured as increase of hospital quality is proportionate to θ for reward function based on achievement. As for achievement with caps, the strongest effect of the incentive is observed at hospitals with median θ. Hospital with high θ do increase their quality, but not as fast as the median types.

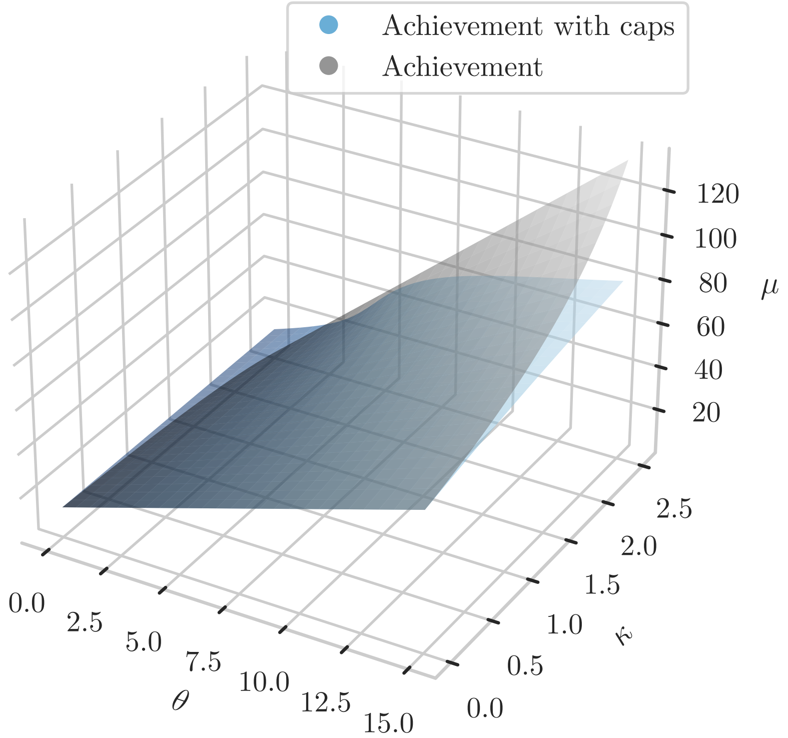
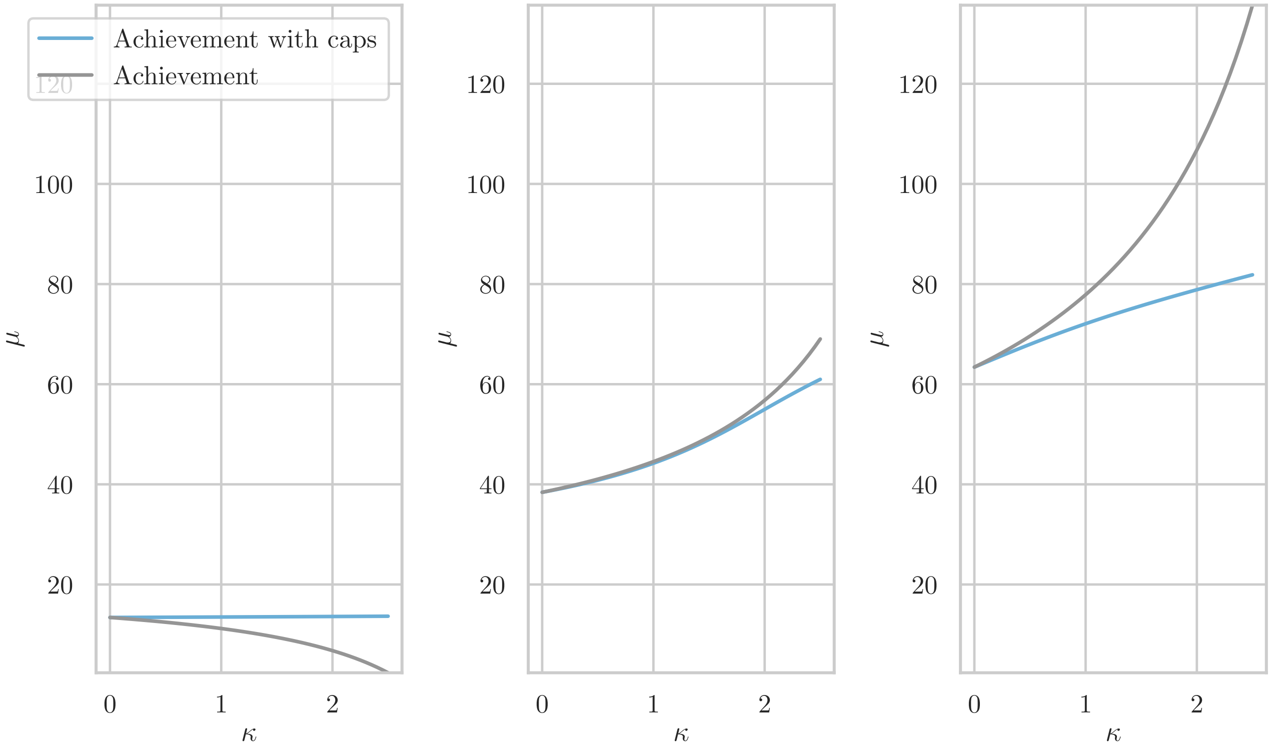


Figure 1: Mean value of the optimal quality μ as the function of θ and κ



(a) $\theta = 0.0$ (b) $\theta = 7.5$ (c) $\theta = 15.0$

Figure 2: Mean value of the optimal quality μ as the function of κ

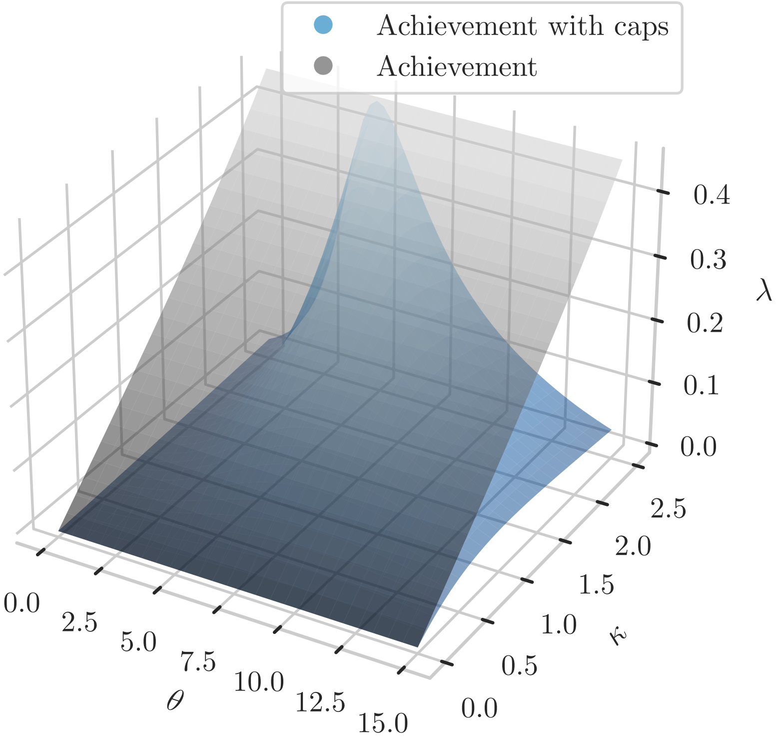


Figure 3: Value of the persistence parameter λ as the function of θ and κ

4.2 Improvement and improvement with cap

Figures 4–6 demonstrate the effect of the parameter κ under the reward based on improvement with cap (red surface) and on improvement (grey surface). We focus on hospitals with different altruistic parameter θ as these groups proxy hospitals with low, median and high baseline quality.

Figure 5 shows plane sections of Figure 4 for low, median and high values of θ. The reform incentive κ has a negligible effect on the mean quality of hospitals with low θ under the schemes based on improvement or improvement with cap. Mean quality of hospitals with median and high θ rises in κ under incentive scheme associated with improvement but goes down under the scheme based on improvement with cap. In both cases the effect is larger for higher θ. Improvement with cap leads to worsening of mean quality due to the fact that hospitals with median and high θ benefit from a temporary decline in quality. Indeed, the increase of quality in the next period implies quality improvement, and hence - a reward for improvement.

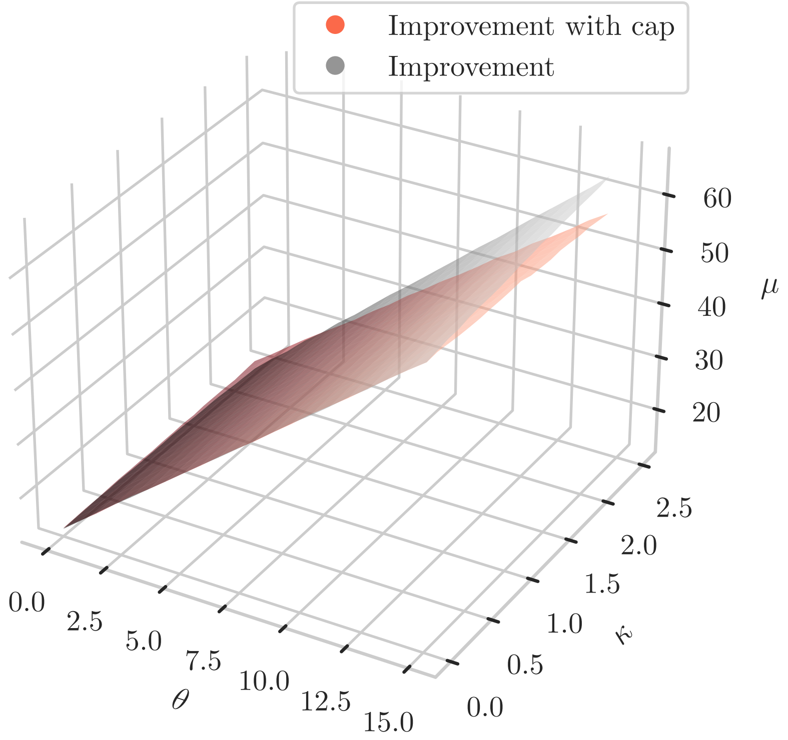
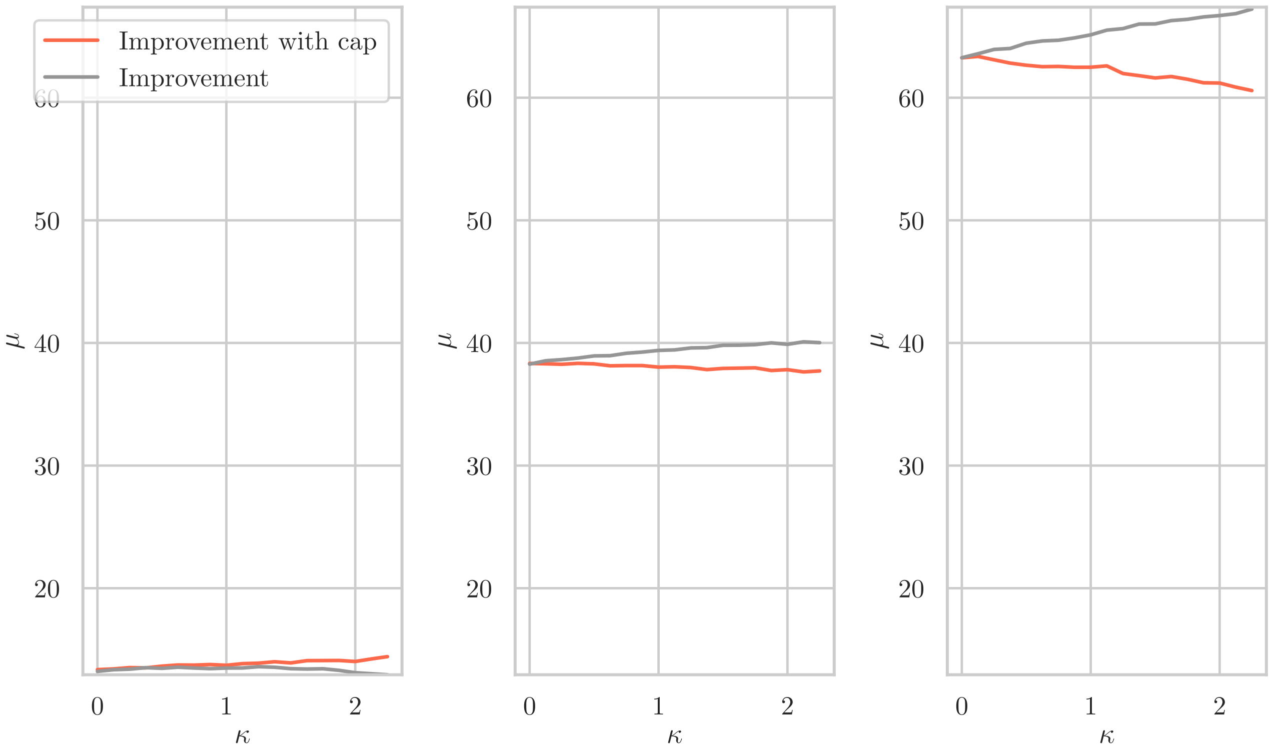


Figure 4: Mean value of the optimal quality μ as the function of θ and κ



(a) $\theta = 0.0$ (b) $\theta = 7.5$ (c) $\theta = 15.0$

Figure 5: Mean value of the optimal quality μ as the function of κ

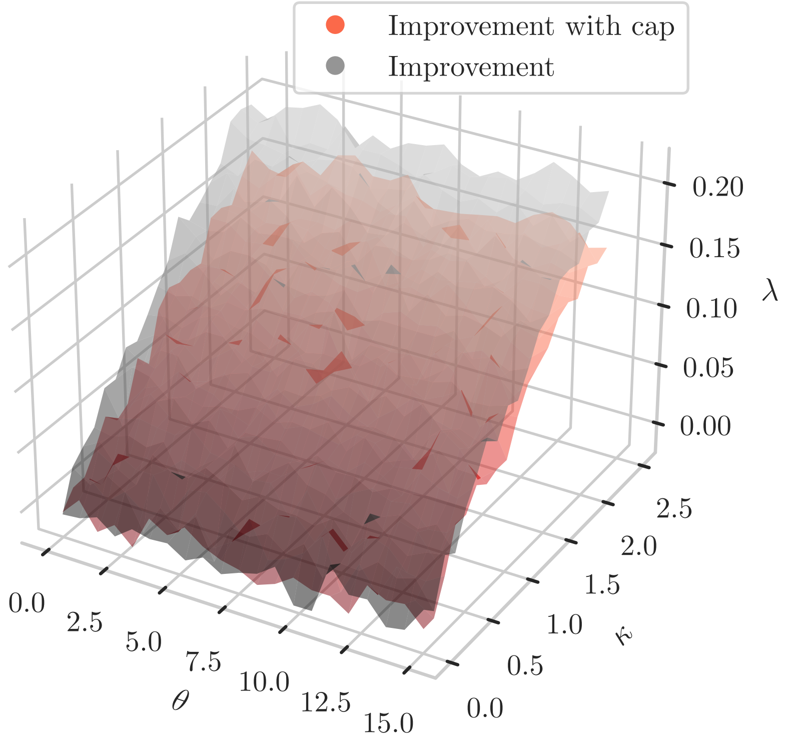


Figure 6: Value of the persistence parameter λ as the function of θ and κ

4.3 Maximum of achievement and improvement

Figures 7–9 demonstrate the effect of the parameter κ under the reward based on the maximum of achievement and improvement (green surface). For comparison, the Figures depict the effect of the incentive linked to achievement with caps (grey surface).

Figure 8 shows plane sections of Figure 7 for low, median and high values of θ. The quality incentive κ has only a slight effect on the mean quality of hospitals with low θ under the reward based on the maximum of achievement and improvement or based on achievement. Mean quality increases in κ for hospitals with median and high θ under each incentive scheme. Measured as the slope of the curve $\mu(\kappa)$, the effects do not differ across the two incentive schemes both for median and high θ. The impact of the incentive when the reward is linked to the maximum of achievement and improvement is larger for hospitals with high θ than for hospitals with median θ. The explanation may be found in the desire of hospitals with median θ to periodically decrease their quality. So in subsequent periods hospitals would restore quality and receive an award related to improvement (which is presumably, larger than the award for their achievement). This motivation, however, does not prevail among these hospitals when the award is based on achievement only. It should be noted that quality decline is unprofitable for hospitals with high θ under the incentive based on the maximum of achievement and improvement. Indeed, these hospitals are in fact stimulated for their high achievement. Moreover, the award for improvement becomes an incentive for these hospitals to raise their quality promptly in case of the unexpected drop in quality.

The effect of incentive scheme measured as increase of hospital quality is the strongest effect at hospitals with median θ for the reward linked to the maximum of achievement and improvement. Hospitals with high θ do increase their quality under this incentive, but not as fast as the median types.

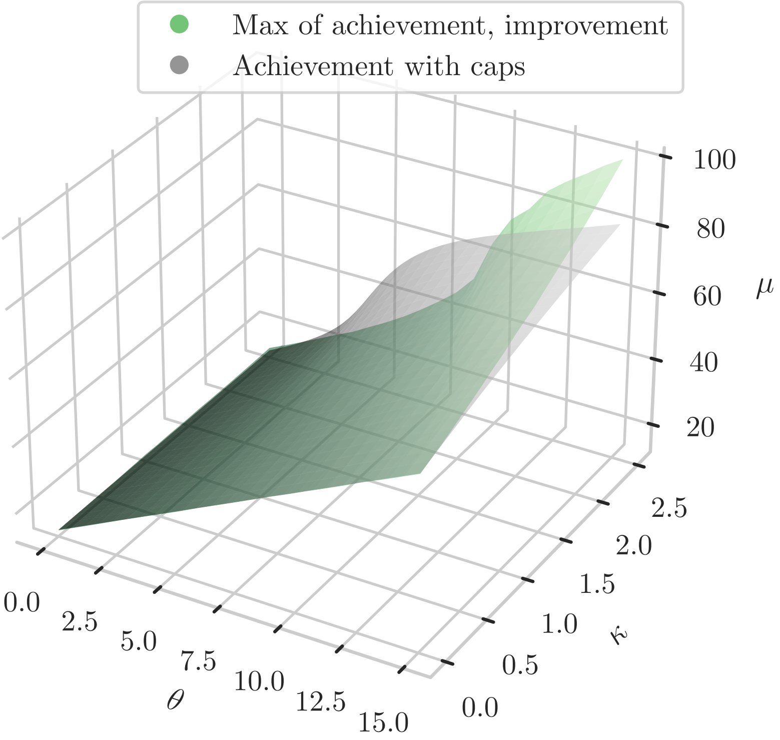
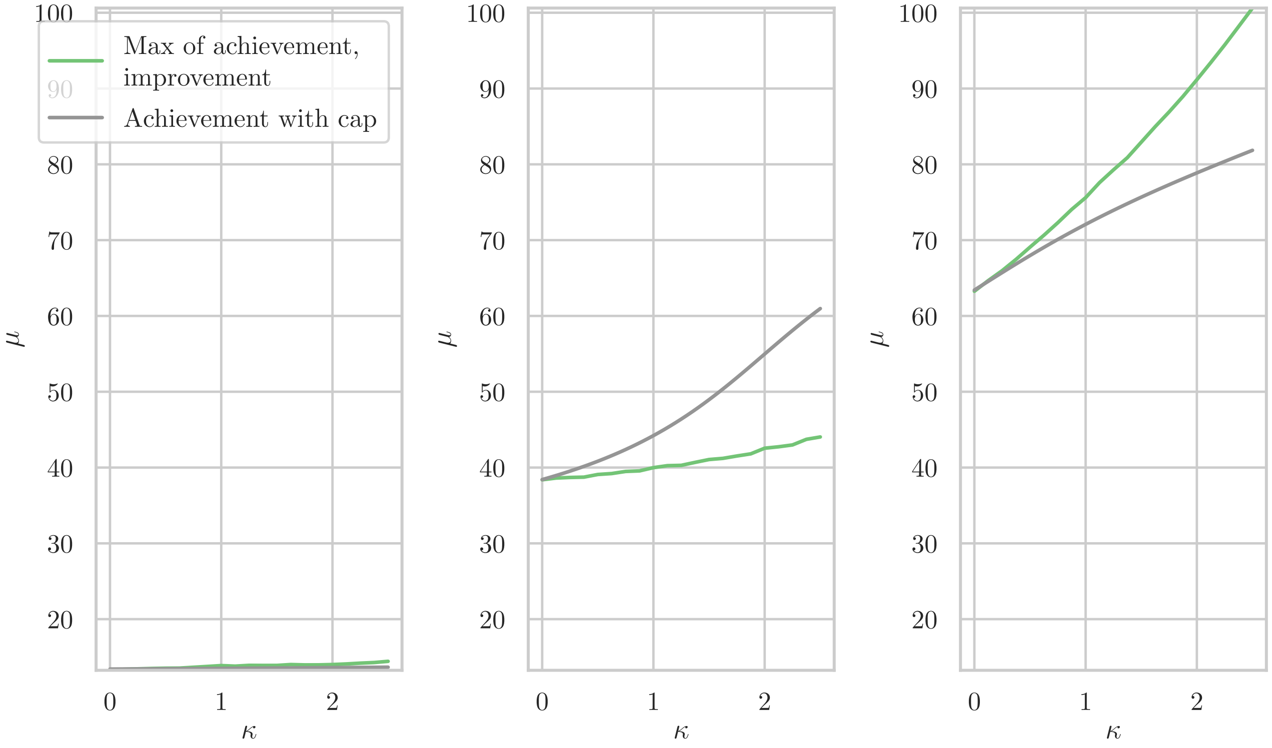


Figure 7: Mean value of the optimal quality μ as the function of θ and κ



(a) $\theta = 0.0$

(b) $\theta = 7.5$

(c) $\theta = 15.0$

Figure 8: Mean value of the optimal quality μ as the function of κ

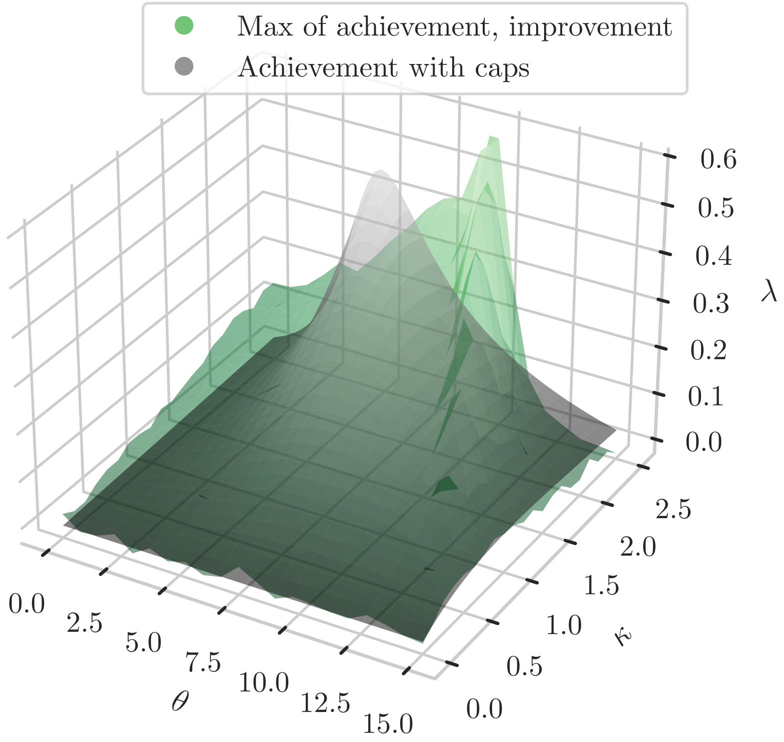


Figure 9: Value of the persistence parameter λ as the function of θ and κ

5 Implications and extensions

5.1 Implications

Remark 12. According to the results of the theoretical model with the reward function linked to achievement, the mean value of measured quality increases in the share of the hospital budget, which is at risk under pay-for-performance (equation (11)). Also, Corollary 7 shows that the type of altruism positively affects the impact of the reform, and that the type of altruism positively influences the hospital's choice of quality.

Remark 13. We obtain that if the regulator rewards improvement then it does not take a fixed share of hospital's budget. It punishes the hospitals with decreasing quality instead. As Corollary 11 and Proposition 8 show that the type of altruism positively affects the impact of the reform, and that the type of altruism positively influences the hospital's choice of quality.

Remark 14. The process for q_t is stable in the theoretical models with achievement and improvement. So hospitals with the highest values of quality q_t show a reduction of quality in the next period: $E(q_{t+1} \mid q_t) < q_t$. The effect is opposite for hospitals with the lowest values of measured quality.

So Equation (7) in the theoretical model may be interpreted as an autoregressive process for the measured quality m_t if the coefficient λ of the lagged dependent variable m_{t-1} is positive and less than one. The autoregressive specification in (7) can be taken equivalent to convergence of the measured quality towards the value $\mu(\theta)$[5] and λ is associated with the speed of quality convergence.

The main reason for the phenomenon of mean reversion is the imprecision of quality measurement, namely, the existence of the random error ε_t in problem (1). Combined with the fact that hospitals make an intertemporal decision within the quality-based reimbursement, the random error causes the autoregressive form of measured quality m_t in (6) and (7).[6]

The regression is less pronounced for higher values of absolute values of the roots of characteristic equations for the process of q_t. Accordingly, since this absolute value increases in α for the model with achievement, and in κ for the model with improvement, the pay-for-performance scheme reduces the phenomenon of regression towards the mean and makes the measured quality more persistent.

Mean reversion makes it incorrect to estimate the effect of pay-for-performance as the net change in the (fitted) value of measured quality at incentivized hospitals. But just this approach is employed in most empirical works that find an inverse relationship between quality improvement and the prior level of measured quality.

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[5] Indeed, rewriting Equation (7) as $E(m_t \mid m_{t-1}, \theta) - \mu(\theta) = \lambda(m_{t-1} - \mu(\theta))$ and assuming $\lambda < 1$, we can see that the expected value of the current measured quality Em_t is closer to the mean value $\mu(\theta)$ than is the value of the measured quality in the previous period, i.e. m_{t-1}.

[6] There may be other causes of the dynamic effect apart from the effect of mean reversion owing to imprecision in quality measurements.

Remark 15. The model becomes static if we assume that $\beta \approx 0$. In this case the hospital does not take account of the future effect of the quality improvement and maximizes only the current value of its utility function. As may be seen from (11)–(14), the size of the pay-for-performance stimulus under budget neutrality still affects the hospital's quality (η_1 and ϕ_1 depend positively on α even if $\beta \approx 0$), but the unconditional mean μ becomes constant and does not depend on α.

5.2 Extensions

5.3 Heterogeneity in hospital production

The model introduced heterogeneity through the hospital-specific parameter θ in the benefit function. An alternative approach incorporates heterogeneity into the cost function of hospitals (Laffont and Tirole, 1993; Mullen et al., 2010), instead of attributing it to altruistic behavior. This alternative formulation does not change the predictions of the model.

Suppose, however, that all components of the utility function are not hospital-specific. Then $\theta \equiv \bar{\theta}$ and the effect of pay-for-performance is homogeneous across hospitals. The differences in the dynamics of m_t for high-quality and low-quality hospitals are only due to imprecision in the quality measurement.

5.3.1 Budget neutrality of the quality incentive scheme

The formulation of the budget neutrality condition in Assumption 1 is close to the true condition of budget neutrality $E(aq_t(\kappa m_t - \alpha)) = 0$ in case of small values of α. Use of the simplified formulation of the budget neutrality condition avoids the unnecessary complexity of the model's solutions. It only negligibly affects the quantitative results for small values of α and does not change our results qualitatively, even for large values of α.

Suppose, however, that the incentive scheme is not budget-neutral. Consider equation (8), which describes the long-term mean value of the quality level of a hospital. In the absence of budget neutrality, κ becomes the varying parameter of policy intensity. The mean effect of pay-for-performance can be shown to increase in κ, while the effect of imprecision in the quality measurement will weaken with the rise in κ. The effect of pay-for-performance is heterogeneous: it is higher for hospitals with higher θ. So absence of budget neutrality of the incentive scheme does not affect the predictions of the model.

5.3.2 Imprecisely measured quality

We assumed that the difference between true quality and its measurable proxy is due to a random error. What if the measurement error is systematic? With the premise that the systematic part of the measurement error is the same for all hospitals, this additional effect would not qualitatively affect the impact of the incentive mechanism.

5.3.3 Consideration of fixed cost of quality improvement

Hospital utility function and the hospital problem

Consider the following augmentation in the hospital's utility function: the hospital can bear a specific amount of fixed cost in order to decrease the variable cost of quality efforts. The utility function can take one of two forms:

$$U_t(m_t, q_t, e_t) = \begin{cases} \theta q_t + a q_t(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t) - C - e_t^2/(2c_1) & \text{if hospital decides} \\ & \text{to bear fixed cost,} \\ \theta q_t + a q_t(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t) - e_t^2/(2c_0) & \text{otherwise.} \end{cases} \tag{21}$$

Here, $C > 0$ and $0 < c_0 < c_1$, so fixed cost alleviates the provision of quality. To concentrate on the effect of fixed cost, we consider a simple one-period model

$$\begin{aligned} &\max_{e_t, q_t, m_t} EU_t(m_t, q_t, e_t) \\ &\text{s.t. } q_t = e_t + \varepsilon_t, \text{ where } \varepsilon_t \sim N(0, \sigma_\varepsilon^2), \\ &\quad m_t \text{ is given.} \end{aligned} \tag{22}$$

The solution

The first order conditions for the two cases are, correspondingly:

$$\begin{aligned} \theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t) - e_t/c_1 = 0 \quad & \text{if costs are payed,} \\ \theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t) - e_t/c_0 = 0 \quad & \text{otherwise.} \end{aligned}$$

Accordingly, the optimal values of effort e_t are:

$$\begin{aligned} e_t^{(1)} &= c_1(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t)) \quad \text{if costs are payed,} \\ e_t^{(0)} &= c_2(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t)) \quad \text{otherwise.} \end{aligned}$$

To select between two strategies: pay the fixed cost and choose $e_t^{(1)}$, or refuse to bear the fixed cost and choose $e_t^{(0)}$ – the hospital has to compare the expected outcomes across the strategies. The expected utility in case of the first strategy is

$$\begin{aligned} EU_t^{(1)} &= e_t^{(1)}(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t)) - C - (e_t^{(1)})^2/(2c_1) \\ &= c_1(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t))/2 - C. \end{aligned}$$

The expected utility under the second strategy equals

$$\begin{aligned} EU_t^{(0)} &= e_t^{(0)}(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t)) - (e_t^{(0)})^2/(2c_0) \\ &= c_0(\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t))/2. \end{aligned}$$

So the first strategy is preferred if $EU_t^{(1)} > EU_t^{(0)}$, or if

$$\theta + a(R_t + p_t(1 + (\kappa m_t - 1)\alpha) - d_t) > \frac{2C}{c_1 - c_0}.$$

Therefore, the effect of the reform (higher α) can be summarized in the following propositions.

Proposition 16. *1. Hospitals split into two groups in the static model with fixed cost. Hospitals pay fixed cost in the group with sufficiently high θ or m_t, and hospitals do not pay fixed cost in another group.*

2. The effect of the reform α is higher for hospitals which pay fixed cost and choose $e_t^{(1)}$ than for hospitals which refuse to bear fixed cost and choose $e_t^{(0)}$. In other words, $\partial e_t^{(1)}/\partial\alpha > \partial e_t^{(0)}/\partial\alpha$.

Proposition 17. *1. The higher the value of α, the more likely is the choice of fixed cost by hospitals with $m_t > 1/\kappa$.*

2. The higher the value of α, the less likely is the choice of fixed cost by hospitals with $m_t < 1/\kappa$.

6 Discussion

Our theoretical and numerical analysis shows that an incentive contract with continuous reward function and consideration of the maximum of achievement and improvement leads to an increase in the mean level of the quality measure at high-quality hospitals. Arguably, this goes in line with the fact that the Medicare quality incentive scheme induces effective quality improvement activities by hospital management,[7] physicians and collaborative groups. Indeed, the results of qualitative surveys similarly reveal that hospital leadership responds to Medicare's value-based purchasing by investment in quality improvements (Smith, 2017, p. 145). Specifically, administrators and medical directors strive to understand "what actions might improve their low scores" (Conrad et al., 2006, p. 447) and admit that without changing the process of care "we would continue to get the same results that we always have" (Jones, 2014, p. 120).

The quality-enhancing efforts at the high-quality US hospitals under Medicare's pilot program and under Medicare's value-based purchasing ensured early diagnosis and timely care,

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[7] E.g. care plan management, complaints registration, incident and infection committees (Wagner et al., 2006).

helped to maintain accurate patient records and encouraged frequent analysis of data in order to assess performance relative to other hospitals (Smith, 2017; Jones, 2014; Grossbart, 2006). Patient satisfaction and clinical outcomes were targeted through establishing a special support team to address pain control and expedite the response to nurse bells, promoting quietness at hospitals by lowering the amount of noise from telephones and stopping the use of pagers at night, educating nurses to use opening and closing phrases to reduce patient anxiety and inform the patient when nurse will be back (Smith, 2017). Other quality improvement activities have been focused on perfecting the quality management system at hospitals by allocating more funds to data coding and information technology (Smith, 2017; Damberg et al., 2009; Wagner et al., 2006; Bentley and Nash, 1998).

Our results suggests strong emphasis on quality activities at high-quality hospitals, and this is indeed discovered in a number of works. For instance, top-performing hospitals in the US pilot program paid more attention to quality enhancement than bottom-performing hospitals (Vina et al., 2009). Under the proportional pay-for-performance mechanism in California, high-quality physicians similarly placed more emphasis on an organizational culture of quality and demonstrate stronger dedication to addressing quality issues than low-quality physicians (Damberg et al., 2009). The desire of high-quality hospitals, which have reached top deciles of hospital performance, to pursue quality improvement by means additional to those proposed by the policy regulator is further evidence in support of our research (Grossbart, 2006).

As well as concentrating on the effect of a pay-for-performance mechanism and its heterogeneity across groups of hospitals of different quality, our theoretical model and numerical analysis focused on the power of the incentive scheme measured as the share of hospital revenue. We discover that higher values of this share (in terms of hospital funds at risk in a budget-neutral scheme) intensify the quality improvement. The finding corresponds to greater effectiveness of larger incentives in comparison with smaller ones, which is found in real-world applications of pay-for-performance (Ogundeji et al., 2016; de Brantes and d'Andrea, 2009; Beaulieu and Horrigan, 2005). Also, if pay-for-performance schemes are voluntary, greater potential rewards encourage participation (de Brantes and d'Andrea, 2009).

There is no general agreement about the optimal size of the incentive, nor is there a clear empirical pattern of the "dose-response relationship", linking financial incentive and quality improvement. The actual share of affected revenue in pay-for-performance schemes varies from 2 to 20% of physician income (Cashin, 2014b; de Brantes and d'Andrea, 2009; Scott, 2007) and from 1 to 9% of hospital income (Bisiaux and Chi, 2014; Sutton et al., 2012; Conrad and Perry, 2009; Rosenthal et al., 2007; Scott, 2007). As regards desirable size of the incentives that would influence behavior of physicians, a survey of HMO managers suggests that the optimal share is in the interval 5–15% of a physician's income (Hillman et al., 1991).

Small incentives may fail to have impact on quality (Ogundeji et al., 2016; Glasziou et al., 2012; Conrad and Perry, 2009; Petersen et al., 2006; Beaulieu and Horrigan, 2005). On the other hand, the power of the incentive scheme must not be excessive. Redistributive programs, which are budget-neutral for the regulator, put a large share of hospital budgets at risk. This brings a danger of serious financial loss and potential damage for low-performing hospitals (Damberg et al., 2014). But when the regulator raises external funds to finance pay-for-performance mechanisms, high power of the incentives scheme may cause other methods of quality improvement to be overlooked (Glasziou et al., 2012). So it is important to evaluate opportunity costs of pay-for-performance through a comparative assessment of alternative designs of incentive stimuli (Meacock et al., 2014; Nahra et al., 2006; Kahn et al., 2006). Such alternatives include various regulatory and managerial initiatives, such as audit, reminders, collaboration and feedback through opinion leaders (Glasziou et al., 2012).

The search for the optimal price for quality of healthcare in terms of parameter κ in the reward function for quality is largely equivalent to finding an optimal size of incentives α. In fact, as is mentioned in the extensions to our model, the concentration of policy literature on the values of α stems largely from the need of the social planner to keep the incentive scheme budget-neutral. So a more general model of a non-budget-neutral pay-for-performance scheme would regard κ as a policy parameter. The approach is implemented in the literature on pay-for-performance in the UK (Kristensen et al., 2016; Sutton et al., 2012).

7 Conclusion

Studies of incentive contracts for healthcare quality usually focus on the mean tendency and give scant attention to potentially heterogeneous response to pay-for-performance by hospitals or physicians at different percentiles of quality distribution. But insufficient theoretical and empirical analysis of such heterogeneity may lead to speculation on the ceiling effects and belief that there are no ways of further improving performance by healthcare providers with better quality.

This paper considered several incentive mechanisms with reward function for quality and provided a theoretical model of dynamic hospital behavior under such remuneration. The predictions of the model show that the incentive mechanisms based on achievement or improvement stimulate all groups of hospitals: there is a direct association between observed quality and its increase in the next period. Larger quality incentives in terms of hospital revenue at risk cause greater increase of observed quality.

The numerical part of the paper shows that mechanisms which have caps or include quality improvement in the reward function may have adverse effects for groups of hospitals. Specifically, the numerical solutions were provided for reward functions with stimulus based on: 1) achievement with caps, 2) improvement with cap, 3) maximum of achievement and improvement. We discover these reward functions have a negligible effect for raising quality of low-quality hospitals. The incentive scheme associated with the maximum or achievement and improvement outperforms the incentive based on achievement at the group of high-quality hospitals. Yet, incorporation of improvement into the reward function has undesirable effects for median quality hospitals: they may temporarily decrease their quality in order to raise it in subsequent periods and receive an award for improvement.

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Appendix A Price-setting in US Medicare's value-based purchasing

The aggregation of scores within domains is conducted as follows. For each hospital i and each measure m in the clinical care, patient experience of care, safety and efficiency domains *achievement points* a_i^m ($0 \leq a_i^m \leq 10$) are calculated as:

$$a_i^m = \begin{cases} 10, & \text{if } y_i^m \geq m_b, \\ \text{Round}\left[\dfrac{9(y_i^m - m_a)}{m_b - m_a} + 0.5\right], & \text{if } m_a \leq y_i^m < m_b, \\ 0, & \text{if } y_i^m < m_a, \end{cases}$$

where y_i^m is the value of measure m for hospital i in the current period, m_b is the benchmark and m_a is the achievement threshold for measure m. The benchmark and achievement threshold are respectively set as the mean of the decile at the best-performing hospital and the median in the empirical distribution of y^m, according to the survey in the baseline period. (The means of the *top* deciles are used as benchmarks for measures of patient experience of care along with survival rate measures of clinical care. The means of the *bottom* deciles are employed for complication/infection measures of safety and spending per beneficiary).

Improvement points p_i^m ($0 \leq p_i^m \leq 9$) for all measures are computed as the difference between the value of the measure in the current period and the baseline period, normalized by the hospital's distance from the benchmark in the baseline period:

$$p_i^m = \begin{cases} 9, & \text{if } y_i^m > m_b, \\ \text{Round}\left[\dfrac{10(y_i^m - y_{i0}^m)}{m_b - y_{i0}^m} - 0.5\right], & \text{if } y_{i0}^m < y_i^m \leq m_b, \\ 0, & \text{if } y_i^m \leq y_{i0}^m, \end{cases}$$

where y_{i0}^m is the score for measure m for hospital i in the baseline period. Note that incentives for improvement apply only to hospitals below the benchmark.

The score for each measure is the maximum of improvement and achievement points: $\max\{a_i^m, p_i^m\}$.

The use of the round function is explained by the desire of Centers for Medicare and Medicaid Services to robustly estimate the point score for each measure and to compare the point scores across the measures with different ranges of their original continuous values.[8]

Additionally, *consistency points* c_i for the patient-experience-of-care domain are calculated as the lowest of the M_P dimension scores d_i^m:

$$c_i = \text{Round}\left[20 \min_m \{d_i^m\} - 0.5\right],$$

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[8] *Federal Register*, Vol.76, No.88. Friday, May 6, 2011. *Rules and Regulations*, p.26518.

where $d_i^m = \dfrac{y_i^m - m_f}{m_a - m_f}$, m_f is the floor for measure (the minimal value across all hospitals) and $m = 1, \ldots, M_P$.

The scores for the clinical care and safety domains are the sum of the values for all quality measures within the domain, divided by the total potential score and translated into percentage points: $d_i^C = \dfrac{\sum_{m=1}^{M_C} \max\{a_i^m, p_i^m\}}{10 M_C} \cdot 100$ for clinical care and $d_i^S = \dfrac{\sum_{m=1}^{M_S} \max\{a_i^m, p_i^m\}}{10 M_S} \cdot 100$ for safety. The score for the efficiency domain is $d_i^E = \max\{a_i^1, p_i^1\} \cdot 100$, where its only measure (spending per beneficiary) is used.

In case of patient experience of care, the domain score is the sum of the values for each measure, divided by the total potential score for quality measures plus the maximum value of consistency points (percentage points): $d_i^P = c_i + \dfrac{\sum_{m=1}^{M_P} \max\{a_i^m, p_i^m\}}{10 M_P} \cdot 80$.

The values of the threshold, floor and benchmark are re-estimated annually, based on the empirical distribution of hospital-level quality measures.

The total performance score of each hospital is a weighted sum of its domain scores: $TPS_i = \sum_{k=1}^{K} w_k d_{ik}$, where K is the number of domains in a given year and weights w_k are established uniform across hospitals (Table 1).

Table 1: Domain weights

Domain	2011	2012	2013	2014	2015	2016	2017	2018	2019
Clinical process of care	0.70	0.45	0.20	0.10	0.05	–	–	–	–
Patient experience of care	0.30	0.30	0.30	0.25	0.25	0.25	0.25	0.25	0.25
Outcome of care (Clinical care from 2016)	–	0.25	0.30	0.40	0.25	0.25	0.25	0.25	0.25
Safety	–	–	–	–	0.20	0.25	0.25	0.25	0.25
Efficiency	–	–	0.20	0.25	0.25	0.25	0.25	0.25	0.25

Note: "–" indicates that a domain is not used in calculation of the total performance score (TPS).
Source: https://www.qualitynet.org/inpatient/hvbp/participation#tab4.

It should be noted that domain weights serve as a tool for placing emphasis on particular groups of measures: greater weight given to a domain implies that the policy-maker is attempting to foster quality increase of measures within this domain, see (Centers for Medicare and Medicaid Services, 2007b). For instance, lower weight for the patient-experience-of-care domain is explained by the subjective character of measures in this domain. The regulator explains reduction of the weight of the clinical-process-of-care domain by the fact that most measures in this domain are already "topped-up", i.e. have reached high threshold and benchmark values (no statistical difference between the 75th and 90th percentiles). Moreover, medical practitioners believe that some clinical-process-of-care measures are not strongly correlated with adverse outcomes for patients. Accordingly, giving more weight to the outcome-of-care domain (with survival rates and complication/infection rates) becomes an attempt at more reasonable approximation of medical quality.

Appendix B Proofs of the model propositions

B.1 Model with achievement

Proof of Proposition 1. Let us find the solution using dynamic programming and method of undetermined coefficients. The state variable in this problem is q_{t-1}. Since the hospital utility function is quadratic, suppose that the value function is quadratic as well:

$$V(q_{t-1}) = \psi_0 + \psi_1 q_{t-1} + \psi_2 q_{t-1}^2 \tag{23}$$

where ψ_0, ψ_1, ψ_2 are undetermined coefficients.

The Bellman's equation for the hospital dynamic optimization problem under Assumption 2 is the following:

$$V(q_{t-1}) = \max_{e_t}\{E_t[U(m_t, q_t, e_t) + \beta V(q_t)]\} \tag{24}$$

where $m_t = q_{t-1}$ and $q_t = e_t + \varepsilon_t$. After substituting $V(q_t)$ from (23) and taking expectations, the expression to maximize becomes the following:

$$(a(R-d) + \theta + ap(1-\alpha+\kappa q_{t-1}))e_t - ce_t^2/2 + \beta(\psi_0 + \psi_1 e_t + \psi_2(e_t^2 + \sigma_\varepsilon^2)). \tag{25}$$

The first order condition is

$$a(R-d) + \theta + ap(1-\alpha+\kappa q_{t-1}) - ce_t + \beta(\psi_1 + 2\psi_2 e_t) = 0. \tag{26}$$

And the value of the efforts is

$$e_t = \frac{a(R-d) + \theta + ap(1-\alpha+\kappa q_{t-1}) + \beta\psi_1}{c - 2\beta\psi_2}. \tag{27}$$

Now we can substitute it to (25), and since e_t is linear in q_{t-1}, this automatically verifies that the quadratic $V(q_{t-1})$ is correct.

Let us find ψ_1 and ψ_2 to complete the proof. After substituting e_t into (24) and equating coefficients for q_{t-1} and q_{t-1}^2 we get the following system of equations for ψ_1 and ψ_2:

$$\begin{cases} \psi_1 = \dfrac{ap\kappa(a(R-d) + \theta + ap(1-\alpha) + \beta\psi_1)}{c - 2\beta\psi_2}, \\ \psi_2 = \dfrac{(ap\kappa)^2}{2c - 4\beta\psi_2}. \end{cases} \tag{28}$$

This system have two solutions which yield the following two possible expressions for e_t:

$$e_t = \mu(\theta) + \frac{2ap\kappa}{c - \sqrt{c^2 - 4\beta(ap\kappa)^2}}(q_{t-1} - \mu(\theta)), \tag{29}$$

or

$$e_t = \mu(\theta) + \frac{2ap\kappa}{c + \sqrt{c^2 - 4\beta(ap\kappa)^2}}(q_{t-1} - \mu(\theta)), \tag{30}$$

where $\mu(\theta) = \dfrac{a(R-d) + \theta + ap(1-\alpha)}{c - ap\kappa(1+\beta)}$ is the same for both (29) and (30). Under Assumption 3

$$0 < \frac{2ap\kappa}{c + \sqrt{c^2 - 4\beta(ap\kappa)^2}} < 1, \quad \text{and} \quad \frac{2ap\kappa}{c - \sqrt{c^2 - 4\beta(ap\kappa)^2}} > \frac{1}{\beta}. \tag{31}$$

This means that only the solution in (30) satisfies the transversality condition

$$\lim_{t\to\infty} \beta^t E\left[\frac{\partial U_t}{\partial m_t} m_t\right] = \lim_{t\to\infty} \beta^t E[ae_t p\kappa m_t] = 0$$

(see Acemoglu (2009), Theorem 16.8). As a result, the optimum value of the hospital efforts is given by (30), and we get the statement of Proposition 1. □

Proof of Corollary 2. By substituting $e_t = q_t - \varepsilon_t$ into (2), we get

$$q_t = \mu(\theta) + \lambda(q_{t-1} - \mu(\theta)) + \varepsilon_t,$$

which is the equation (6). □

Proof of Corollary 3. Since the autoregressive process in (6) is stable, it converges to a stationary autoregressive process defined by the same equation.

Given that $E(\varepsilon_t \mid q_{t-1}, \theta) = 0$, we immediately get (7) for the expectation conditional on θ. Equation (8) immediately follows from the law of iterated expectation $E(q_t \mid \theta) = E(E(q_t \mid q_{t-1}, \theta) \mid \theta)$, the fact that $E(q_{t-1} \mid \theta) = E(q_t \mid \theta)$ for a stationary process, and equation (7). □

Proof of Corollary 4. The statement immediately follows from the law of iterated expectation $E(q_t) = E(E(q_t \mid \theta))$, and equation (8). □

Proof of Corollary 5. The equation (10) follows directly from assumptions 3, 1, and Corollary 4. □

Proof of Proposition 6. The condition $E(\kappa m_t - \alpha) = 0$ from Assumption 1 implies that $\kappa = \alpha/\mu$. Substituting $\kappa = \alpha/\mu$ into equation (9), we obtain (11), into equation (4), we obtain (12). The inequalities $0 < \phi_1 < 1$ directly follow from (31) and Assumption 3. Straightforward differentiation with respect to α shows that μ, η_1 and ϕ_1 are increasing in α. As for η_1, it decreases in α for sufficiently large values of $\bar{\theta}$. □

Proof of Corollary 7. The equation (15) directly follows from (3) in Proposition 1 after substituting (12) and (13) there. The statement about derivatives is the direct implication of the fact that the derivative in θ equals η_1, and the latter increases in α due to Proposition 6. □

B.2 Model with improvement/deterioration

Proof of Proposition 8. Let us find the solution using dynamic programming and method of undetermined coefficients. The state variable in this problem is q_{t-1}, q_{t-2}. Since the hospital utility function is quadratic, suppose that the value function is quadratic as well:

$$V(q_{t-1}, q_{t-2}) = \psi_0 + \psi_1 q_{t-1} + \psi_2 q_{t-1}^2 + \psi_3 q_{t-2} + \psi_4 q_{t-2}^2 + \psi_5 q_{t-1} q_{t-2} \tag{32}$$

where ψ_0, ψ_1, ψ_2, ψ_3, ψ_4, ψ_5 are undetermined coefficients.

The Bellman's equation for the hospital dynamic optimization problem under Assumption 2 is the following:

$$V(q_{t-1}, q_{t-2}) = \max_{e_t}\{E_t[U(m_t, q_t, e_t) + \beta V(q_t, q_{t-1})]\} \tag{33}$$

where $m_t = q_{t-1} - q_{t-2}$ and $q_t = e_t + \varepsilon_t$.

Let us define $A = a(R-d) + \theta + ap(1-\alpha)$ and $B = ap\kappa$ for brevity. After substituting $V(q_t, q_{t-1})$ from (32) and taking expectations, the expression to maximize becomes the following:

$$\begin{aligned}(A + B(q_{t-1} - q_{t-2}))e_t - ce_t^2/2& \\ + \beta(\psi_0 + \psi_1 e_t + \psi_2(e_t^2 + \sigma_\varepsilon^2) + \psi_3 q_{t-1} + \psi_4 q_{t-1}^2 + \psi_5 e_t q_{t-1}).&\end{aligned} \tag{34}$$

The first order condition is

$$A + B(q_{t-1} - q_{t-2}) - ce_t + \beta(\psi_1 + 2\psi_2 e_t + \psi_5 q_{t-1}) = 0. \tag{35}$$

And the value of the efforts is

$$e_t = \frac{A + B(q_{t-1} - q_{t-2}) + \beta(\psi_1 + \psi_5 q_{t-1})}{c - 2\beta\psi_2}. \tag{36}$$

Now we can substitute it to (34), and since e_t is linear in q_{t-1} and q_{t-2}, this automatically verifies that the quadratic form of $V(q_{t-1}, q_{t-2})$ is correct.

Let us find ψ_2, ψ_4 and ψ_5 to complete the proof. After substituting e_t into (33) and equating coefficients for q_{t-1}^2, q_{t-2}^2 and $q_{t-1}q_{t-2}$ we get the following closed system of equations for ψ_2, ψ_4 and ψ_5:

$$\begin{cases} \psi_2 = \dfrac{B^2 + 2B\beta\psi_5 - 4\beta^2\psi_2\psi_4 + \beta^2\psi_5^2 + 2\beta c\psi_4}{-4\beta\psi_2 + 2c} \\ \psi_4 = \dfrac{B^2}{-4\beta\psi_2 + 2c} \\ \psi_5 = \dfrac{-B^2 - B\beta\psi_5}{-2\beta\psi_2 + c} \end{cases} \tag{37}$$

Introduce $x = \frac{c - 2\beta\psi_2}{B\beta}$, so $\psi_2 = \frac{c - B\beta x}{2\beta}$. The system becomes the following:

$$\begin{cases} \frac{-B\beta x + c}{2\beta} = \frac{B}{2\beta x} + \beta\psi_4 + \frac{\psi_5}{x} + \frac{\beta\psi_5^2}{2Bx} \\ \psi_4 = \frac{B}{2\beta x} \\ \psi_5 = -\frac{B + \beta\psi_5}{\beta x} \end{cases} \tag{38}$$

This system leads to the following equation for x:

$$\frac{B\left(\beta\left(x+1\right)^2 - 2x + \left(x+1\right)^2 - 1\right) + x\left(x+1\right)^2\left(B\beta x - c\right)}{2\beta x\left(x+1\right)^2} = 0$$

and the following expression for e_t:

$$e_t(x) = \frac{A(x+1)}{B\beta(\beta x + \beta + x^2)} + \frac{q_{t-1}}{\beta(x+1)} - \frac{q_{t-2}}{\beta x}.$$

There are four solutions for x:

$$x_1 = \frac{1}{4}\left(D - 2 - \sqrt{\left(\sqrt{(D+2)^2 - 4R} - (D-2)\right)^2 - 16} - \sqrt{(D+2)^2 - 4R}\right) \tag{39}$$

$$x_2 = \frac{1}{4}\left(D - 2 + \sqrt{\left(\sqrt{(D+2)^2 - 4R} - (D-2)\right)^2 - 16} - \sqrt{(D+2)^2 - 4R}\right) \tag{40}$$

$$x_3 = \frac{1}{4}\left(D - 2 - \sqrt{\left(\sqrt{(D+2)^2 - 4R} + (D-2)\right)^2 - 16} + \sqrt{(D+2)^2 - 4R}\right) \tag{41}$$

$$x_4 = \frac{1}{4}\left(D - 2 + \sqrt{\left(\sqrt{(D+2)^2 - 4R} + (D-2)\right)^2 - 16} + \sqrt{(D+2)^2 - 4R}\right) \tag{42}$$

where $R = 1/\beta$ and $D = c/B\beta$. Under Assumption 3 $D > (1+\beta)^2/\beta \geq 2$, which means that roots x_1 and x_2 are complex, so they are to be dropped. Also, it can be noticed that $\beta x_4 > 1$ and $\beta x_3 < 1$, which means that the solution $e_3(x_3)$ is unstable and does not satisfy the transversality condition

$$\lim_{t\to\infty} \beta^t E\left[\frac{\partial U_t}{\partial m_t} m_t\right] = \lim_{t\to\infty} \beta^t E[a e_t p \kappa \alpha m_t] = 0$$

(see Acemoglu (2009), Theorem 16.8). The solution $e_t(x_4)$ satisfies the transversality condition, which leads to the statement of Proposition 8. □

Proof of Corollary 9. By substituting $e_t = q_t - \varepsilon_t$ into (16), we get

$$q_t = \mu(\alpha,\kappa,\theta) + \phi_1(\alpha,\kappa)(q_{t-1} - \mu(\alpha,\kappa,\theta)) + \phi_2(\alpha,\kappa)(q_{t-2} - \mu(\alpha,\kappa,\theta)) + \varepsilon_t.$$

which is the equation (17). The difference equation has the following characteristic equation:

$$1 - \frac{\lambda}{\beta(x+1)} + \frac{\lambda^2}{\beta x} = 0.$$

For x substituted from (42) this equation have two complex roots, which absolute values are the same and increase in κ. This finishes the proof. ☐

Proof of Corollary 3. Since the autoregressive process in (17) is stable, it converges to a stationary autoregressive process defined by the same equation.

Given that $E(\varepsilon_t \,|\, q_{t-1}, \theta) = 0$, we immediately get (18) for the expectation conditional on θ. Equation (19) immediately follows from the law of iterated expectation $E(q_t \mid \theta) = E(E(q_t \mid q_{t-1}, \theta) \,|\, \theta)$, the fact that $E(q_{t-1} \,|\, \theta) = E(q_t \,|\, \theta)$ for a stationary process, and equation (18). ☐

Proof of Corollary 11. The statement immediately follows from the law of iterated expectation $E(q_t) = E(E(q_t \,|\, \theta))$, and equation (19). ☐

Appendix C Robustness to functional form assumptions

C.1 Hospital's utility function in general form

The model in Section 3 employs a linear demand for hospital services, a linear benefit from altruism and a linear marginal disutility of quality-inducing efforts. Here we relax these assumptions about the functional form. Specifically, we assume that the demand for hospital services $Q(q_t)$ is monotonically increasing and concave in hospital quality: $Q(q_t) > 0$, $Q'(q_t) > 0$, $Q''(q_t) \leq 0$; the benefit from altruism $u(q_t)$ is monotonically increasing and concave in hospital quality: $u'(q_t) > 0$, $u''(q_t) \leq 0$; and the disutility of efforts $C(e_t)$ is an increasing and convex function: $C'(e_t) > 0$, $C''(e_t) > 0$. The one-period utility of the hospital becomes

$$U_t(m_t, q_t, e_t) = \theta u(q_t) + Q(q_t)(R_t + p_t(1 - \alpha + \kappa m_t) - d_t) - C(e_t)$$

and the first order condition under constant prices and unit costs of healthcare services from Assumption 2 is

$$E_t[\theta u'(q_t) + Q'(q_t)(R - d + p(1 - \alpha + \kappa m_t)) - C'(q_t) + \beta Q(q_{t+1}) p\kappa] = 0,$$

which leads to the following nonlinear difference equation for q_t:

$$\theta u'(q_t) + Q'(q_t)(R - d + p(1 - \alpha + \kappa(q_{t-1} + \varepsilon_t))) - C'(q_t) + \beta p\kappa E_t[Q(q_{t+1})] = 0. \tag{43}$$

We cannot solve this equation directly, so we linearize it along a non-stochastic steady state.

C.2 Mean value

In order to calculate the mean value for the stationary solution of the linearized equation, we rewrite the first order condition (43) for the constant $q_t \equiv q$ and $\varepsilon \equiv 0$:

$$\theta u'(q) + Q'(q)(R - d + p(1 - \alpha + \kappa q)) - C'(q) + \beta p \kappa Q(q) = 0. \tag{44}$$

Solve equation (44) with respect to q, denote the solution as μ. Note that $\mu = \mu(\alpha, \theta)$ and the equation is nonlinear, so only a numerical solution is feasible in the general case.

Using the implicit function theorem, we can compute

$$\frac{\partial \mu}{\partial \theta} = -\frac{u'(\mu)}{\theta u''(\mu) + Q''(\mu)(R - d + p(1 - \alpha + \kappa \mu)) + Q'(\mu) p \kappa - C''(\mu) + \beta p \kappa Q'(\mu)}, \tag{45}$$

$$\frac{\partial \mu}{\partial \alpha} = -\frac{-Q'(\mu) p}{\theta u''(\mu) + Q''(\mu)(R - d + p(1 + (\kappa \mu - 1)\alpha)) + Q'(\mu) p \kappa - C''(\mu) + \beta p \kappa Q'(\mu)} \tag{46}$$

and

$$\frac{\partial \mu}{\partial \kappa} = -\frac{Q'(\mu) p \mu + Q(\mu) \beta p}{\theta u''(\mu) + Q''(\mu)(R - d + p(1 + (\kappa \mu - 1)\alpha)) + Q'(\mu) p \kappa - C''(\mu) + \beta p \kappa Q'(\mu)}. \tag{47}$$

The numerators of (45) and (47) are greater than zero, and the numerator of (46) is less than zero. The denominators of (45), (46) and (47) are less than zero for sufficiently high values of $C''(\mu)$. Therefore the mean optimal quality level increases in the level of altruism θ and the degree of incentive κ and decreases in α (given that κ is constant).

Adding the budget neutrality condition from Assumption 1, we get the equation $\mu = \alpha / \kappa$. Differentiating it we get

$$\frac{\partial \kappa}{\partial \alpha} = -\frac{\kappa \dfrac{\partial \mu}{\partial \alpha} - 1}{\mu + \kappa \dfrac{\partial \mu}{\partial \kappa}} > 0,$$

so the incentive size increases along with the share of hospital's budget at risk. This implies that

$$\frac{\partial \mu(\kappa(\alpha), \alpha, \theta)}{\partial \alpha} = \frac{\partial \mu}{\partial \kappa} \cdot \frac{\partial \kappa}{\partial \alpha} + \frac{\partial \mu}{\partial \alpha} = \frac{\dfrac{\partial \mu}{\partial \kappa} + \mu \dfrac{\partial \mu}{\partial \alpha}}{\mu + \kappa \dfrac{\partial \mu}{\partial \kappa}} > 0.$$

The last inequality follows from (46) and (47).

The mixed partial derivative under budget-neutrality condition is

$$\frac{\partial^2 \mu(\kappa(\alpha), \kappa, \theta)}{\partial \alpha \partial \theta} = \frac{\left(1 - \kappa \dfrac{\partial \mu}{\partial \alpha}\right) \dfrac{\partial}{\partial \theta} \left(\mu \dfrac{\partial \mu}{\partial \kappa}\right) + \mu \dfrac{\partial^2 \mu}{\partial \theta \partial \alpha} \left(\mu + \kappa \dfrac{\partial \mu}{\partial \kappa}\right)}{\left(\mu + \kappa \dfrac{\partial \mu}{\partial \kappa}\right)^2}$$

which means that if the second partial derivative $\dfrac{\partial^2 \mu}{\partial\theta\partial\alpha}$ is negative and sufficiently large in its absolute value then the sign of $\dfrac{\partial^2 \mu(\kappa(\alpha), \kappa, \theta)}{\partial\theta\partial\alpha}$ can be negative (it can happen for large values of θ if $u'''(\mu) > 0$).

C.3 Cycle around the mean

Denote $\tilde{q}_t = q_t - \mu$. Then the linearized first order condition becomes

$$\begin{aligned} Q'(\mu)p\kappa\tilde{q}_{t-1} + (\theta u''(\mu) + Q''(\mu)(R - d + p(1 - \alpha + \kappa\mu)) + Q'(\mu)p\kappa - C''(\mu))\tilde{q}_t \\ + \beta p\kappa Q'(\mu)E_t\tilde{q}_{t+1} = -Q'(\mu)p\kappa\varepsilon_t. \end{aligned} \tag{48}$$

The value of the persistence parameter λ is determined by the characteristic equation of (48). Similarly to the main model, there are two real roots for the characteristic equation of (48) for sufficiently large values of $C''(\mu)$. One of the roots must be discarded because of the transversality condition. The other root determines how persistent the deviations of measured quality from the mean value are in the steady state.

Note that in contrast with Section 3, λ depends on θ in nonlinear case. This means that the regression analysis allows us to estimate the average value of the persistence parameter λ.

C.4 Numerical solution

The figures 10–12 are plotted for $u(q_t) \propto q_t^{0.75}$, $Q(q_t) \propto q_t^{0.85}$, $C(q_t) \propto q_t^2$ to demonstrate typical behavior of the mean value $\mu(\alpha, \theta)$, its derivative $\partial\mu/\partial\alpha$ (presented as an increment $\Delta\mu = \mu(\alpha) - \mu(\alpha - \Delta)$ for $\Delta = 0.001$) and the value of the persistence parameter $\lambda(\alpha, \theta)$. The figures illustrate that the pay-for-performance effect, albeit non-linear, still has all the properties of the effect in the main model: it is positive, monotonically increases in α and in θ. The persistence parameter λ also increases in α.

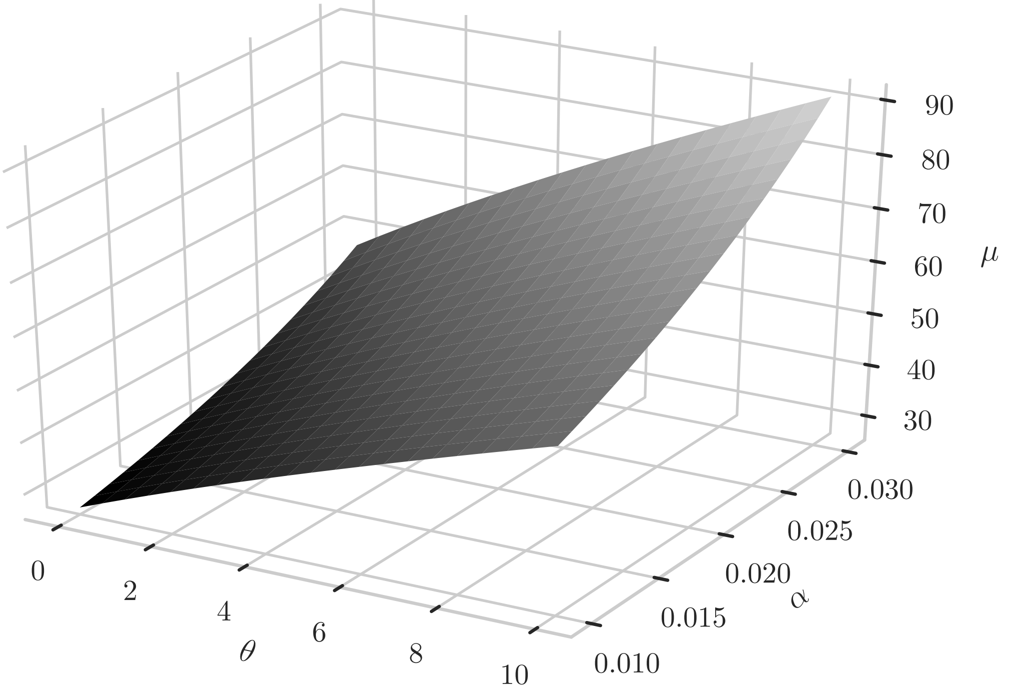

Figure 10: Mean value of the optimal quality μ as the function of θ and α

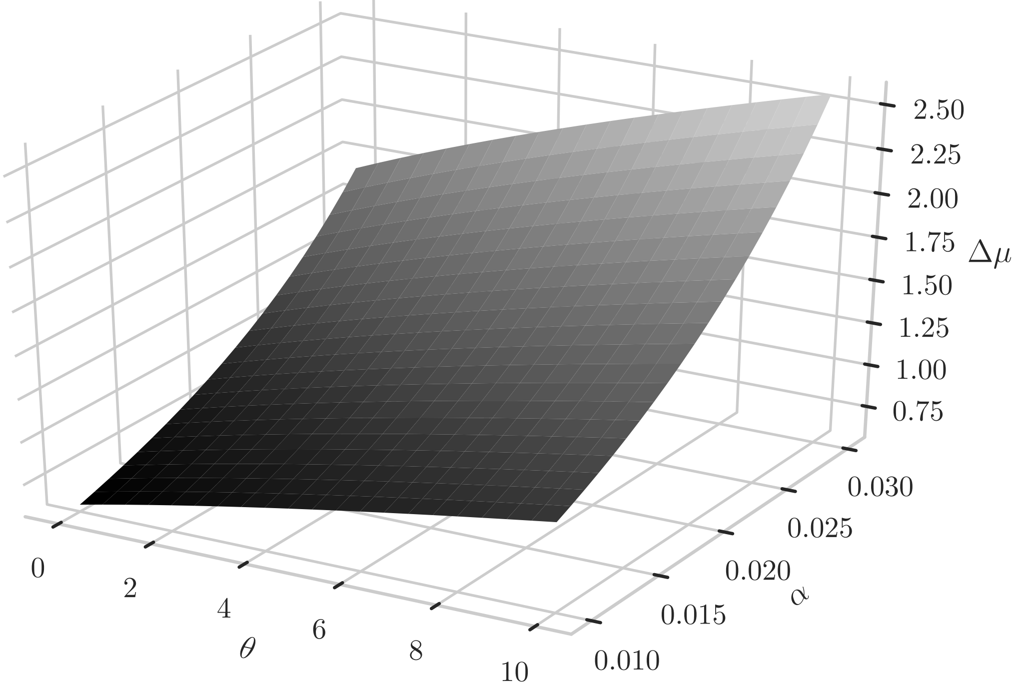

Figure 11: Increment of the mean value of the optimal quality to an increase in α on 0.001 $\Delta\mu$ as the function of θ and α

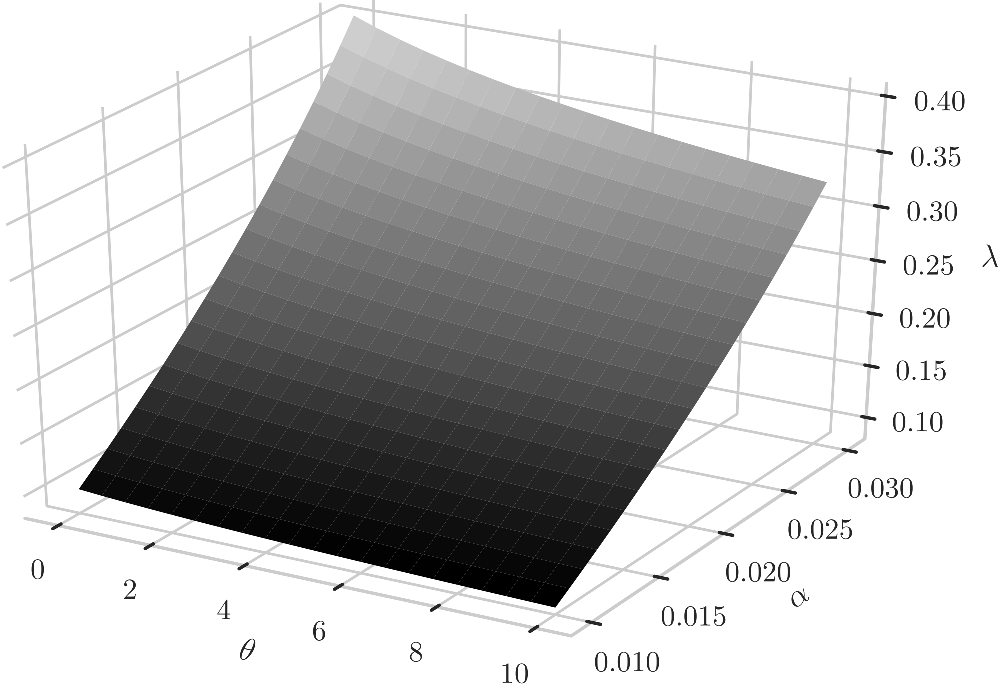

Figure 12: Value of the persistence parameter λ as the function of θ and α