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PROFIT SHARING AND INVESTMENT BY REGULATED UTILITIES: A WELFARE ANALYSIS

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Profit sharing and investment by regulated utilities: a welfare analysis*

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Abstract

We analyse the effects of different regulatory schemes (price cap and profit sharing) on a firm's investment of endogenous size. Using a real option approach in continuous time, we show that profit sharing does not delay a firm's start-up investment relative to a pure price cap scheme. Profit sharing does not necessarily affect total investment either, if the threshold for profit sharing is high enough. Only a profit sharing intervening for low profit levels may delay further investments. We also evaluate the effects of profit sharing on social welfare, determining the level of profit that should optimally trigger tighter regulation: profit sharing should be less stringent in sectors where there are bigger investment opportunities.

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1 Introduction

The performance of regulated utilities has raised concern about how to reconcile consumer protection and the incentive to invest. The most popular solution among regulators is the (by now traditional[1]) $RPI-x$ scheme, which makes the regulated price insensitive to cost-reducing investments: in this way, firms which reduce their costs are not immediately penalized. However, sometimes this rule allows the firm to keep huge profits, and there are now many cases where price cap regulation is modified with an earnings sharing clause, whereby if profits are too high there is an automatic mechanism which revises prices to the benefit of consumers (Sappington, 2002). On the other hand, such a redistribution of benefits from the firms to the consumers has been accused of decreasing the incentive to invest (among others, Weisman (1993) or Lyon (1996) and Mayer and Vickers (1996)), although the evidence is fairly mixed[2].

Our paper contributes to this debate using modern investment theory, which stresses the importance of irreversibility, and calls for a set-up where investment timing and uncertainty play a substantial role.[3] While previous theoretical results show that profit sharing decreases the incentive to invest, the results we obtain may explain the ambiguity of the empirical evidence, in that we show that profit sharing schemes may or may not decrease investment, depending on the actual level of profit which triggers profit sharing.

An additional contribution of the paper is that we carry out a fully-fledged welfare analysis which allows us to identify when the potential losses from profit sharing (delayed investment) are more than compensated by the gains

[1] According to this scheme, the regulated price should start from a given level, and then increase at a rate equal to the difference between the expected inflation rate (the Retail Price Index, RPI) and an exogenously given component (x). See Beesley and Littlechild (1989).

[2] See, for example, Ai and Sappington (2002) and Gasmi et al. (1999). The fact that in several cases profit sharing may lead to greater efficiency relative to other forms of regulation (e.g. a pure price cap) raises a problem, given that the existing theory indicates otherwise.

[3] Investment timing is often left to the firm's discretion. For instance, upon the request of the EC, McKinsey conducted an assessment of 3G licenses in the European Union. Some contracts did not even mention a timing for service launch (Germany, The Netherlands, Sweden). In the UK the date of service launch was explicitly left to the operators' commercial discretion. In those Member States with short-term rollout requirements, delay relaxations already occurred. Similar relaxations are also expected in Member States with longer-term requirements (European Commission, 2002).

in terms of allocative efficiency and welfare distribution (higher consumer surplus). The optimal level at which profit sharing should intervene can thus be characterised. As long as marginal productivity of capital does not decrease too slowly, profit sharing is always optimal even if it delays investment. Profit sharing should intervene at higher levels of profit when investment opportunities are bigger and when the weight of profits in the welfare function is higher.

This paper is linked to two streams of literature. The first one is the traditional theory of investment under regulation, where investment ("effort") is modelled in a static framework where the firm knows exactly the return from its investment (e.g. Laffont and Tirole, 1986). The same approach was taken by several papers which compare price caps and profit sharing rules, showing that a pure $RPI - x$ system provides better incentives to invest relative to a price cap with profit sharing (e.g. Lyon, 1996).[4]

However, while investment in managerial effort is typically reversible, investment in physical assets is not. When irreversibility matters, a static model is no longer appropriate and the decision to invest should be modelled in a dynamic framework, where the option value of investment is explicitly considered. We operate along this line, and we show that what matters to investment is not profit sharing per se, but the profit level which triggers profit sharing: a "soft" profit sharing constraint does not reduce the incentive to invest.

The second stream of literature is the one on investment and irreversibility (Dixit and Pindyck, 1994), which introduces real options. However, only a few articles in this area derive policy implications using this setting. A notable exception is Dixit (1991), who shows that a price ceiling affects one-off investment strategies by perfectly competitive firms only if it is low enough. Although consistent with our result, Dixit's finding does not refer to a natural monopoly and above all it does not include an earnings sharing clause in the price constraint.

Real option techniques are used more and more in analysing regulated sectors. For instance, Hausman and Myers (2002) claim that over the 1997-2000 period the revenues of the three major U.S. railroads were inadequate, since the existing regulatory constraint did not take correct account of sunk

[4] Weisman (1993) shows that when price cap rules incorporate an element of profit sharing, price caps may even represent a worsening relative to a pure cost-based regulation, a notoriously inefficient set-up.

costs and irreversible investment. A similar point is made by Pindyck (2004),[5] who criticizes the U.S. Telecommunications Act of 1996 as it "ignores the basic fact that sunk costs do matter in decision-making when those costs have yet to be sunk" [p.12][6]. Another interesting contribution is Teisberg (1993), who studies rate of return regulation. More recently, Panteghini and Scarpa (2003a) use a simple framework to show that modifying a price cap with an element of profit sharing does not affect the incentive to make an investment of a given amount. However the above articles are based on the assumption that the investment size is exogenous.

Along this line, a particularly relevant paper is Dobbs (2004), which analyses price cap regulation of a firm endowed with market power, and shows that a monopoly firm generally under-invests. While Dobbs concentrates on the effects of an optimal price cap, here we compare different regulatory schemes. In this set-up, we investigate how the two regimes we consider affect investment. Moreover, we perform a welfare analysis, which allows us to derive optimally the profit level which should trigger earnings sharing.

The paper is organised as follows. The next section introduces the basic continuous time model. Section 3 studies an investment of endogenous size, made by a natural monopolist, under both price cap and profit sharing regulation. Section 4 provides a welfare analysis, while the final section summarizes the results and discusses possible extensions.

2 The model

We consider a regulated utility (e.g. a gas distributor or a motorway concessionaire) which has to decide whether, when and how much to invest in a new project. After the initial investment, the utility can upgrade it, with further extensions or quality improvements which have a (set-up) cost, but increase the (variable) profit margin of the firm. The investment is irreversible, in that its cost cannot be recovered.

The timing of the investment is decided by the firm. As this utility faces uncertainty (the potential demand varies over time in a way which is hard to forecast) it may thus postpone the investment to a moment in which it feels

[5] On this point see also Evans and Guthrie (2005).

[6] There is also mounting evidence of how much real options can affect investment decisions in the energy sector. See, for example, Keppo and Lu (2003), Saphores *et al.* (2004), Hlouskova *et al.* (2005) and Nasakkala and Fleten (2005).

relatively safer about its profitability.

In order to study such an investment problem and its relationship with both uncertainty and irreversibility, the minimum ingredients of the model must include a stochastic element and a dynamic structure, where time plays an explicit role. This calls for a dynamic stochastic model, which may be formally complex, but is however necessary to study both uncertainty and irreversibility. Following an established literature,[7] we thus apply a continuous time model of investment for a firm, subject to a regulatory constraint on its price. The following assumptions are introduced.

Demand Market demand at time t is an isoelastic function of price p_t

$$q(p_t;\gamma_t) = \gamma_t p_t^{-\eta}, \tag{1}$$

with $\gamma, \eta > 0$. Time is a continuous variable.

The firm Only one firm operates in this market, maximizing expected profits over an infinite time horizon. In each t, its payoff is

$$\Pi_t = \Psi(K_t) p_t q_t \tag{2}$$

where $K_t \in (0, \overline{K}]$ is the firm's asset or "capital", where $\overline{K}$ represents the maximum efficient investment that the current technology allows.[8] The function $\Psi(K_t)$ describes the effects of capital accumulation on the firm's profitability. This term can be thought of as a mark-up, so that investment can be interpreted either as cost-reducing or as quality-enhancing. On this term we assume $\Psi(0) = 0$, $\Psi(\overline{K}) \leq 1$, $\Psi_K > 0$ and $\Psi_{KK} < 0$.

Regulation On the new project considered (e.g. a new motorway or railway line) the monopolist is subject to price regulation, and we consider two alternatives. The basic one is an $RPI - x$, whereby if the firm starts producing at time zero, the initial price $p_0 > 0$ is given, and price dynamics are defined by the difference between the inflation rate (changes in the retail price index, RPI) and an exogenous factor x_l :

$$p_t = p_0 e^{(RPI - x_l)t}. \tag{3}$$

[7]The traditional reference is Dixit and Pindyck (1994).

[8]The value of $\overline{K}$ may or may not be finite (in some cases, it may be so large that its existence becomes irrelevant). None of the following results depend on this. For a discussion on limited expandability, see Dixit and Pindyck (2000).

The second alternative we consider is profit sharing, whereby when profits reach a given threshold, $\widetilde{\Pi}$, a higher x factor applies[9]. Profit sharing is therefore defined as a modification of (3), as follows

$$p_t = p_0 e^{(RPI - x_j)t} \quad \text{where } x_j = \begin{cases} x_l & \text{if } \Pi \leq \widetilde{\Pi}, \\ x_h & \text{if } \Pi > \widetilde{\Pi}, \end{cases} \tag{4}$$

with $x_l < x_h$. These parameters are known in advance by all market participants, and they are set irreversibly.

Uncertainty Demand uncertainty is a crucial matter for regulated firms.[10] We model this aspect assuming that the parameter γ_t in (1) is stochastic and follows a geometric Brownian motion

$$d\gamma_t = \sigma_q \gamma_t dz_t, \tag{5}$$

where σ_q is the variance parameter, and dz_t is the increment of a Wiener process satisfying the conditions that $E(dz_t) = 0$ and $E(dz_t^2) = dt$. Therefore $E(d\gamma_t) = 0$ and $E(d\gamma_t^2) = (\sigma_q \gamma_t)^2 dt$. This means that, starting from $\gamma_0 > 0$, the random position of γ_t at time $t > 0$ has a normal distribution with mean γ_0 and variance $\gamma_0^2(e^{\sigma^2 t} - 1)$, which is increasing in t.

Our model focuses on demand uncertainty. It is worth noting that introducing uncertainty on the productivity of investment in the form of technical obsolescence would not affect the quality of results.[11]

[9] There are other possibilities for modelling profit sharing; see Sappington and Weisman (1996) and Schmalensee (1989) for (qualitatively analogous) formulations.

[10] For instance, highway traffic is largely beyond the franchise holder's control, its forecasts are notoriously imprecise, especially in the long term (Engel, Fisher and Galetovic, 2001). Something similar holds for railways investments. See for instance World Bank and Inter-American Development Bank (1998, p. 75) on the Argentine experience, where the study concludes that "Given the lower-than-expected traffic levels, the investment amounts agreed in the contracts are likely to be unnecessary and uneconomic".

[11] This claim can be supported by an analogy with the problem analysed in Panteghini (2005), who studies the effects of an asymmetric tax scheme, whereby only "excess" profits are taxed. This paper studies incremental and sequential investments made by a representative firm, assuming that the lifetime of investment is stochastic and subject to technical obsolescence. When the investment project expires, the firm gets an option to restart. According to Bernanke's (1983) Bad News Principle, it is shown that the asymmetric tax scheme does not affect the firm's decisions. This suggests that the same holds for profit sharing, which also entails an asymmetric extraction of profits.

Investment Given that price is regulated, investment is the main decision undertaken by the firm. The vast literature on investment theory (e.g., Dixit and Pindyck, 1994) points out that investment decisions entail two interrelated issues: how much to invest, and when. We thus assume that the firm has an intial investment opportunity (of endogenous amount and timing) and that the firm can further expand its capital at any future instant t. The optimal choice by the firm thus entails a whole investment profile (how much to invest at each point in time).

Once invested, K is irreversible, in that it can be increased but not decreased. Investment is therefore a sunk cost. Unlike the traditional industrial organization literature on sunk costs, we do not consider a one-off investment decision whose amount and timing are given, but a sequence of decisions in continuous time. The explicit introduction of time is important to capture the very notion of profit sharing. A purely static model would not be appropriate to analyse the effects of a regulatory constraint which may vary over time depending on profits.

Profit dynamics Investment decisions are driven by profits. Given that Ψ and p are deterministic while demand is uncertain, (5) implies that current profits include all relevant information about future profitability and are thus crucial in inducing a firm to invest. Therefore, it becomes very important to analyse how profits evolve over time.

To this end, we first derive the dynamics of the demand function. Given (1), (5) (3) and (4), it is straightforward to obtain

$$dq_t = \alpha_{qj} q_t dt + \sigma_q q_t dz_t, \tag{6}$$

where $\alpha_{qj} \equiv -\eta\,(RPI - x_j)$, $j = l, h$. Defining the firm's revenues as $\Theta_t \equiv p_t q_t$, using equations (2), (3) and applying Itô's lemma, as shown in the Appendix, we can finally write the profit dynamics as

$$\begin{aligned} d\Pi_t &= \Psi_K(K(t))\Theta(t)dK + \Psi(K(t))d\Theta(t) \\ &\equiv \Gamma(K_t)\Pi_t dK_t + \Pi_t[\alpha_j dt + \sigma dz_t], \end{aligned} \tag{7}$$

where $\alpha_j \equiv (1-\eta)\,(RPI - x_j)$ is the expected growth rate, $\sigma = \sigma_q$ is the standard deviation, while $\Gamma(K_t) \equiv \Psi_K\,(K_t)\,/\Psi(K_t) > 0$ captures the direct effect of investment on the mark-up. From (7), we can see that in each t

investment affects the level of profit through the marginal mark-up factor, which depends on the stock of capital. In particular if no new investments are undertaken, $dK = 0$ and profits are driven only by demand changes and the price cap.

In the next section we will focus on the investment decisions of a regulated firm. For simplicity, hereafter, we will omit the time variable t.

3 The investment decision

The firm's problem is one of choosing optimal capital accumulation by maximizing the expected present value of profits $\Pi(K,\Theta) \equiv \Psi(K)\Theta$, taking into account both profit sharing regulation as well as the value of $\overline{K}$. Defining p_K as the price of capital we can write the firm's problem

$$V(K,\Theta) = \max_K E_0\left[\int_0^\infty e^{-rt}[\Pi(K,\Theta) - p_K dK]dt \mid K_0 = K,\ \Theta_0 = \Theta\right],$$
$$s.t.\ dK \geq 0, \text{with } K \in (0,\overline{K}] \text{ and (7) for all } t. \tag{8}$$

where $E_0[\cdot]$ is the expectation operator. Function $V(\cdot)$ is assumed to be twice continuously differentiable. The expectation in equation (8) is taken with respect to the joint distribution of K and Θ and it is conditional on the information available at time zero taking into account the profit sharing constraint and the irreversibility constraint.[12]

Without installation costs, the rate of growth of capital is unbounded where dK is the investment process. These expansions are also assumed to be irreversible.[13]

Solving problem (8) we can prove the following:

[12] The dynamics of Θ are described in the Appendix (see (18)).

[13] Technically, this means that, by exercising the option to delay, the firm acquires a compound option to expand, which consists of a continuum of American call options, each for any dK. For any given starting value of capital, the firm can exercise a call option to expand capital. After the exercise of such an option, the firm obtains another American call option allowing it to undertake a further increment. The compound option is completely exercised when the firm reaches $\overline{K}$.

Proposition 1 *The firm invests (increases K) every time current profit goes beyond* $\Pi^*(K)$, *which is defined as follows:*

$$\Pi^*(K) \equiv \begin{cases} \Pi^*_{PC}(K) \equiv \rho(x_l) p_K \frac{\Psi(K)}{\Psi_K(K)}, & \text{for } K \in (0, \widetilde{K}], \\ \Pi^*_{PS}(K) \equiv \rho(x_h) p_K \frac{\Psi(K)}{\Psi_K(K)}, & \text{for } K \in (\widetilde{K}, \overline{K}]. \end{cases} \tag{9}$$

where $\widetilde{K}$ *is the amount of capital such that*

$$\Pi^*_{PC}(\widetilde{K}) = \widetilde{\Pi}, \tag{10}$$

and where

$$\rho(x_j) \equiv \left[\frac{\beta_1(x_j)}{\beta_1(x_j)-1}\delta(x_j)\right], \text{ with } \rho(x_l) < \rho(x_h),$$
$$\beta_1(x_j) = \frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 1,$$
$$\delta(x_j) \equiv r - \alpha_j \text{ for } j = l, h.$$

Proof. See Appendix. ■

Proposition 1 describes the effects of regulation on capital accumulation. The interpretation of Proposition 1 is that profit sharing is neutral for low levels of investment ($K < \widetilde{K}$). Only incremental investments raising capital beyond $\widetilde{K}$ will be delayed. Notice that $\widetilde{K}$ is endogenous but it does not vary over time.

As shown in Proposition 1, investment depends on x_l and neither on x_h nor on the switch point $\widetilde{K}$ (and, equivalently, on $\widetilde{\Pi}$).[14] As profit sharing does not affect the initial investment decision, the neutrality result found in Panteghini and Scarpa (2003a) in a two-period set-up is confirmed.

To better analyse the investment profile over time, it is convenient to make use of Figure 1 below. Notice that while the profit sharing threshold $\widetilde{\Pi}$ is a constant, the optimal investment trigger value $\Pi^*(K)$ is a function of K. Since the marginal profitability of K is decreasing, this function is increasing.

[14] If $\widetilde{\Pi}$ were below this trigger point, the price scheme would already start with $x_j = x_h$ and the two regulatory regimes would in practice coincide. This would not be a very interesting case, since the two regimes would collapse to a price cap one with x_h. In order to have an actual alternative to price cap, we must assume that $\widetilde{\Pi}$ is larger than the trigger point. In this way, regulation starts with a value of $x_j = x_l$, which is made more stringent at a later stage, if profit goes beyond $\widetilde{\Pi}$.

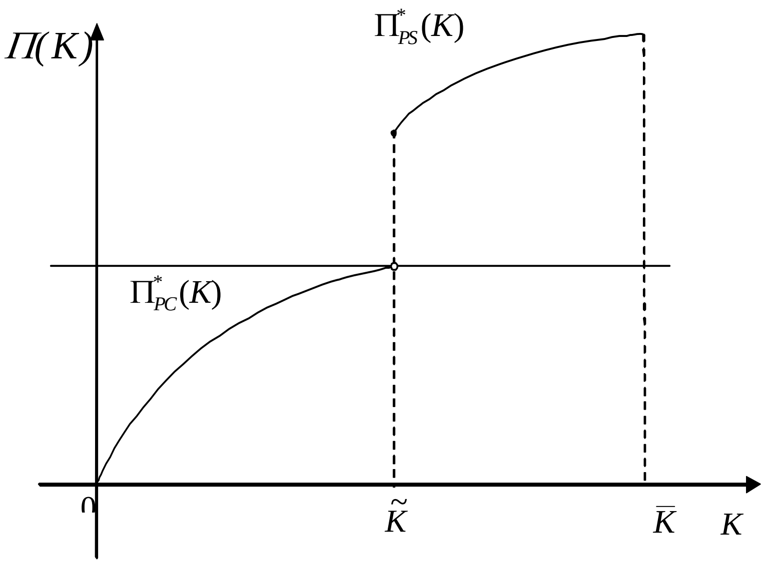

Fig. 1

Figure 1: Capital accumulation K as a function of current profit Π. As current profit goes beyond $\widetilde{\Pi}$, price regulation gets tighter and only a higher profit level, $\Pi^*_{PS}(\widetilde{K})$, will induce further investment.

For $K \in (0, \overline{K})$ the investment function determined in (9) consists of two parts.

The first one, for $K \in (0, \widetilde{K}]$, indicates that the firm increases capital when current profits go beyond the trigger point denoted by $\Pi^*_{PC}(K)$ in (9) for any value of K. This function does not depend on x_h, i.e. it does not depend on the existence of a profit sharing scheme (and would thus emerge in the optimal investment policy with a pure price cap).

The second part shows that profit sharing affects investment only when K reaches $\widetilde{K}$. As $\rho(x_h) > \rho(x_l)$, $\Pi^*_{PS}(\widetilde{K}) > \Pi^*_{PC}(\widetilde{K})$. This implies that the level of current profit, required to convince the firm to expand its plant, jumps upwards when $K = \widetilde{K}$. Profit sharing, by increasing the value of the current profit beyond which the firm decides to expand its plant, delays further investment.

More precisely, when current profits reach the threshold $\widetilde{\Pi}$ for the first time, K is increased to $\widetilde{K}$. Further marginal increases in Π, however, will not be sufficient to trigger further investments: when current profits happen to be in the interval $[\widetilde{\Pi}; \Pi^*_{PS}(\widetilde{K})]$, the firm will not increase capital beyond $\widetilde{K}$. Given the tighter regulatory constraint, further investments would be justified only when demand is so high that $\Pi > \Pi^*_{PS}(\widetilde{K})$. Only at this point will the firm find it optimal to increase K: given that current profit is the best estimate of future profit, for high current profit levels giving up market opportunities would be too expensive. When K reaches its maximum level $\overline{K}$, further investments are impossible and the firm can only produce at the regulated price.[15]

If the firm already has a given capital level K but demand conditions worsen so that current profit falls below $\Pi^*_{PC}(K)$, given irreversibility, the optimal policy is not to invest (keeping K constant). The firm waits until profits move above $\Pi^*_{PC}(K)$ and at this point it will invest in order to keep profits in line with the optimal policy curve (9). This happens as long as $\Pi^*_{PC}(K) < \Pi < \Pi^*_{PC}(\widetilde{K}) = \widetilde{\Pi}$, and the new capital level remains below the threshold given by $\widetilde{K}$.

As for uncertainty, notice that an increase in the standard deviation σ is equivalent to a mean-preserving spread,[16] so that we measure uncertainty

[15] Quite obviously, if $\widetilde{K} \geq \overline{K}$, profit sharing never interferes with investment decisions and $\Pi^*(K) = \Pi^*_{PC}(K)$ for all relevant values of K. In this case, a loose profit sharing constraint would be neutral with respect to investment decisions.

[16] In order to see that the quality of results would not change, we could add to (5) another

through σ. It is thus straightforward to see that an increase in this parameter increases the term $\rho(x_j)$ via $\beta_1(x_j)$, for $j = l, h$. This raises the optimal threshold $\Pi^*(K)$ for any given K, so that greater uncertainty implies lower willingness to invest by the firm (Dixit and Pindyck, 1994, p. 369-370).[17]

4 Welfare analysis

So far, we have seen that profit sharing may discourage investment if it intervenes for low levels of profit. In terms of social welfare, however, this negative effect may be offset by the positive effect of profit sharing on consumer surplus. In this section, we first determine the net welfare effect of profit sharing regulation. We will then compute the optimal switch level $\widetilde{\Pi}^*$.

The starting point of our welfare analysis is the following standard welfare function:

$$W(x_l, x_h; \widetilde{\Pi}) = S(x_l, x_h; \widetilde{\Pi}) + \lambda V(x_l, x_h; \widetilde{\Pi}), \qquad (11)$$

where S is the consumer surplus, V is the firm's value and $\lambda \leq 1$ is the weight of profits in the welfare function (in line with the standard regulation literature since Baron and Myerson, 1982).

Our welfare analysis starts from a basic trade-off. Profit sharing, which entails a quicker decrease in prices, increases consumer surplus. However, unless the threshold $\widetilde{\Pi}$ is very high, profit sharing may delay investment, which given the price dynamics has no effect on consumers but does affect the firm's profit. Is profit sharing desirable? Can we identify an optimal value for $\widetilde{\Pi}$? We try and answer these questions by analysing in turn the two main arguments of the welfare function.

Let's now compute the firm's value. It is straightforward to show the following.

Wiener process, uncorrelated with dz_t, i.e.: $\frac{d\gamma_t}{\gamma_t} = \sigma dz_t + \Delta\sigma dw_t$, and $E(dz_t dw_t) = 0$. Given its properties, the expected value $E(d\gamma_t)$ is still nil, while the variance is $E(d\gamma_t^2) = (\sigma^2 + \Delta\sigma^2){\gamma_t}^2 dt$. For further details on this point see, for example, Abel (1985).

[17] Capital irreversibility and demand uncertainty highlight the fact that the possibility of deciding when and whether to invest is highly valuable to the firm. Without uncertainty, the investment decision collapses to a problem of optimal timing where the firm determines immediately the preferred time for phasing the investment.

Lemma 1 *For any initial value of* $K < \widetilde{K}$*, the firm's value may be written as*

$$V(x_l, x_h; \widetilde{\Pi}) = V^{PC}(x_l) + \Delta V^{PS}(x_l, x_h; \widetilde{\Pi}), \tag{12}$$

where $V^{PC}(x_l)$ *is the project value under pure price-cap regulation, and* $\Delta V^{PS}(x_l, x_h; \widetilde{\Pi}) < 0$ *represents the decrease in the firm's value due to profit sharing.*

Proof. See Appendix. ■

As shown in the Appendix,

$$\Delta V^{PS}(x_l, x_h; \widetilde{\Pi}) = A^{PS}(K; x_l, x_h)\Theta^{\beta_1(x_l)},$$

where $A^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv -\epsilon c\left(\overline{K}\right)\widetilde{\Pi}^{1-\beta_1(x_l)}$, $\epsilon \equiv \frac{\delta(x_h)-\delta(x_l)}{\delta(x_l)\delta(x_h)} > 0$, and $c\left(\overline{K}\right) \equiv \int_{z=K}^{\overline{K}} \Psi_K(z)\Psi(z)^{\beta_1(x_l)-1}dz > 0$, so that $A^{PS}(x_l, x_h; \widetilde{\Pi}) < 0$. The expected loss due to a profit sharing regulation intervenes only as Π reaches the threshold $\widetilde{\Pi}$. The term ϵ represents the effects of the tighter regulation which follows profit sharing. The formula for $\Delta V^{PS}(x_l, x_h; \widetilde{\Pi})$ shows that the loss in the firm's value is proportional to the expected value of the incremental investments which the firm decides to delay because of profit sharing.

This means that the value of the firm is negatively affected by profit sharing, relative to a pure price cap: it is easy to verify that $\frac{\partial V^{PS}(K,\Theta)}{\partial \widetilde{\Pi}} > 0$ (a more relaxed profit constraint increases the firm's value). To some extent, this is natural, in that the very notion of profit sharing comes from the idea that a scheme which yields an excessively imbalanced distribution of rents is undesirable[18].

The consumer surplus under profit sharing can be computed considering the present discounted value of the integral below the demand function. Profit sharing affects consumer surplus through its effect on price. Given that profit sharing may or may not take place, depending on whether or not profits go beyond $\widetilde{\Pi}$, consumer surplus - analogously to V - embodies the future value of what can be obtained at a later stage because of profit sharing. As shown in the Appendix, we can prove the following.

Lemma 2 *For any given value of* $\widetilde{K} < \overline{K}$*, the present value of consumer surplus may be written as*

$$S(x_l, x_h; \widetilde{\Pi}) = S^{PC}(x_l) + \Delta S^{PS}(x_l, x_h; \widetilde{\Pi}), \tag{13}$$

[18] Note that also the rate-of-return regulation scheme, still prevailing in a large part of the US, is based on the idea that restraining monopoly rents is a goal in itself.

where $S^{PC}(x_l)$ is the consumer surplus under price cap regulation and $\Delta S^{PS}(x_l, x_h; \widetilde{\Pi})$ is the increase in consumer surplus due to profit sharing.

Proof. See Appendix. ■

As shown in the Appendix, $S^{PC}(x_l)$ is a perpetual rent which depends on price but does not directly depend on K: consumer surplus depends on the regulated price, which in turn depends on the firm's choices only when they are such as to trigger profit sharing. The term

$$\Delta S^{PS}(x_l, x_h; \widetilde{\Pi}) = B^{PS}(x_l, x_h; \widetilde{\Pi})\Theta^{\beta_1(x_l)},$$

with the constant $B^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv \epsilon \left(\frac{\widetilde{\Pi}}{\Psi(K)}\right)^{1-\beta_1(x_l)}$, represents the expected value of the increase in the consumer surplus due to profit sharing (and $\Delta S^{PS}(x_l, x_h; \widetilde{\Pi}) = 0$ for $x_l = x_h$, when no profit sharing takes place). Given that $\beta_1(x_l) > 1$, an increase in $\widetilde{\Pi}$ decreases consumer surplus: if profit sharing takes place "later", consumers' welfare is lower. Analogously, an increase in x_h increases $\Delta S^{PS}(x_l, x_h; \widetilde{\Pi})$.

Taking account of (12) and (13), the welfare function (11) can be written as

$$W(x_l, x_h; \widetilde{\Pi}) = W^{PC}(x_l) + \Delta W^{PS}(x_l, x_h; \widetilde{\Pi}), \tag{14}$$

where $W^{PC}(x_l) \equiv S^{PC}(x_l) + \lambda V^{PC}(x_l)$ is the welfare level under pure price-cap and $\Delta W^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv \Delta S^{PS}(x_l, x_h; \widetilde{\Pi}) + \lambda \Delta V^{PS}(x_l, x_h; \widetilde{\Pi})$ measures the benefit arising from profit sharing. Profit sharing may or may not be desirable, depending on the sign of $\Delta W^{PS}(x_l, x_h; \widetilde{\Pi})$, and thus we concentrate on this term. As shown in the Appendix, the following holds

Proposition 2 *The net benefit from profit sharing is*

$$\Delta W^{PS}(x_l, x_h; \widetilde{\Pi}) = \epsilon \widetilde{\Pi}^{1-\beta_1(x_l)} \left[\Psi(\widetilde{K})^{\beta_1(x_l)-1} - \lambda c\left(\overline{K}\right)\right] \Theta^{\beta_1(x_l)}. \tag{15}$$

Proof. See Appendix. ■

As shown in Proposition 2, profit sharing may have a positive or negative impact on welfare ($\Delta W^{PS} \gtreqless 0$). In line with intuition, the welfare gain due to profit sharing decreases with λ, i.e. the weight attached to the firm's profit. For similar reasons, the term $c\left(\overline{K}\right)$, which measures the ability of the possible expansion of investment to decrease costs, also enters with a negative sign. As shown in Proposition 1, profit sharing may delay investment, and when the potential positive effects of investment opportunities are substantial, profit sharing may decrease welfare.

The effect of profit sharing also depends on the actual value of $\widetilde{\Pi}$, and our analysis allows us to determine the optimal level that should trigger profit sharing. The regulator's problem is one of choosing

$$\widetilde{\Pi}^{*} = \arg\max \Delta W^{PS}\left(x_l, x_h; \widetilde{\Pi}\right).$$

To find a closed-form solution we assume that $\Psi(K)$ is a Cobb-Douglas function, i.e. $\Psi(K) = K^{\varepsilon}$ with $\varepsilon \in (0,1)$. As shown in the Appendix, we prove the following:

Proposition 3 *Let $\widetilde{\Pi}^{*}$ be the optimal level of profit which triggers profit sharing, i.e. the threshold point ensuring the condition*

$$MS = MC, \tag{16}$$

where $MS \equiv (1-\varepsilon)\Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-1}$, $MC \equiv \lambda \cdot c\left(\overline{K}\right)$, *and* $\widetilde{K} \equiv \left[\frac{\lambda c\left(\overline{K}\right)}{1-\varepsilon}\right]^{\frac{1}{\varepsilon[\beta_1(x_l)-1]}}$.

If ε is low enough ($\varepsilon < 1 - \frac{\lambda}{\beta_1(x_l)}$) the optimal level of profit $\widetilde{\Pi}^{*}$ is finite.

Proof. See Appendix. ■

As shown in (16), the LHS of (16) measures the marginal consumer surplus (MS), while the RHS is the weighted marginal cost (MC), i.e. the product between λ and the firm's marginal option value. Using (16) it is straightforward to obtain

$$\widetilde{\Pi}^{*} = \rho(x_l)\frac{p_K \widetilde{K}}{\varepsilon}. \tag{17}$$

This level can be seen as the product between the rate of return (adjusted for irreversibility) $\rho(x_l)$ and the cost of the "critical" investment (adjusted for productivity) $\frac{p_K \widetilde{K}}{\varepsilon}$. This means that, if the marginal productivity of investment decreases sufficiently quickly, a regulatory scheme with a profit sharing element is preferable to a pure price cap scheme. On the contrary, when ε is large enough, the marginal productivity of capital does not decrease very sharply as K increases, and delaying capital accumulation causes a more substantial welfare loss.

To get a better intuition of the result, let us finally analyse the determinants of $\widetilde{\Pi}^*$. Results of comparative statics exercises are summarised in Table 1.

Table 1: the determinants of $\widetilde{\Pi}^*$

	MS	MC	$\widetilde{\Pi}^*$
σ	+	+	?
λ	0	+	+
$\overline{K}$	0	+	+

The first element we can look at is uncertainty, namely the standard deviation of demand (σ). Its effect is twofold. On the one hand, an increase in demand uncertainty raises the firm's option value and, therefore, the required minimum return (ρ). On the other hand, given the capital level, a higher volatility of demand increases the marginal consumer surplus; consumers benefit from the firm's good news (which may trigger a higher value of the x factor) without suffering at the margin due to the bad news. Therefore uncertainty has an ambiguous effect on $\widetilde{\Pi}^*$.

A higher value of the weight of profit in the welfare function (11) tends to increase the optimal value of $\widetilde{\Pi}$ through its effect on $\widetilde{K}$; given that consumer surplus matters less to social welfare, the incentives to invest become more important to social welfare and profit sharing should intervene at a later stage.

A similar effect occurs when $\overline{K}$ rises. If profit sharing discourages investments, then its negative impact on welfare is higher, when investment opportunities are more relevant (i.e. the maximum possible level of capital $\overline{K}$ is larger). When $\overline{K}$ is large, a high level of $\widetilde{\Pi}$ is useful to delay this negative effect.

5 Conclusions and extensions

Our paper has shown how profit sharing does not delay a firm's start-up investment relative to a pure price cap scheme. Profit sharing does not necessarily affect total investment either, if the threshold for profit sharing is high enough. We have also identified conditions under which "some" profit sharing is actually optimal, stressing that profit sharing should be less stringent in sectors where there are bigger investment opportunities.

Uncertainty is essential to this result, in that without it, investment levels (even with irreversibility) only depend on a very standard definition of their profitability as the value of waiting is zero. With uncertainty, the expected net present value of an investment depends on the option value, which is positive because of uncertainty. This leads to the bad news principle (Bernanke, 1983), which in turn is what drives our key result.

It is worth stressing that profit sharing is usually subject to three related but distinct criticisms, which can be discussed in our framework, namely that profit sharing (i) reduces the incentive to innovate, (ii) leads a firm to hide its profit through appropriate accountancy practices or (iii) through direct increases in costs. Let us analyse them separately.

In the light of our results, the statement that profit sharing leads to inefficiency and lack of investment (or innovation) should be qualified. We have seen that if the profit sharing threshold is too low, this regulatory scheme may indeed delay improvements. Thus, the presence of a dis-incentive to invest in innovations depends on how tight the profit constraint is. In industries in particular, where innovation is crucial, this potential welfare loss should be seriously considered.

Coming to the second claim, namely that profit sharing leads to accountancy manoeuvers aimed at hiding profits in order to avoid the tightening of regulatory constraints, we have to consider the following. Manipulating the accounts in order to avoid or delay profit sharing is a natural consequence of any mechanism which relates regulation to the financial performance of a firm. Therefore, any regulation based on the firm's accounts must consider some additional control in the form of forcing the firm to keep regulatory accounts separate (and strictly monitored). In practice, however, it is unclear whether this is a peculiarity of profit sharing. Even "pure" price cap schemes need to have a periodic price review, during which an assessment of a firm's cost is always carried out. In this perspective, the difference between profit sharing and a pure price cap seems to be mainly the frequency of such controls.

It should be noted, however, that *per se* these possible accounting tricks are not directly inefficient (apart from their implications on the effectiveness of regulation and on its cost). In this respect, the third common claim, that profit sharing leads to unnecessarily high costs ("gold plating"), is even more serious in that - if this were the case - then profit sharing would entail a clear inefficiency. This effect could actually emerge if profit sharing took place with a delay, so that decreasing our profits in the current year would allow us another year of "softer" regulation, in which higher profits could possibly more than compensate the current "waste" of money. Introducing such delays in a dynamic model like the one we presented, would mean working either within a discrete-time framework or with differential and difference equations at the same time - one thing which in principle is perfectly feasible but in practice quite cumbersome.

Note again, however, that even firms subject to a pure price cap with periodic price reviews may be tempted to do the same. As price reviews are carried out on the basis of the accounts of a specific year, if the accounts considered for the price review show high costs, then the price review should be more favourable to the firm. Moreover, if a firm manages to obtain a higher price, the consequences of this achievement refer to the whole regulatory period (between one price review and the next one). Therefore, the temptation to inflate costs in the year considered for the review are particularly high, as the high cost in one year should be traded off against higher prices for the following years (usually 3 to 5 years). The general problem is that even pure price caps in practice embody elements of profit evaluation (if not explicit sharing) and this reduces the practical differences between the two models.

Despite its apparent complexity, necessary to incorporate uncertainty and time in a realistic way, the model still rests on somehow restrictive assumptions. However, it is easy to show how the model can accommodate at least two additional factors.

Regulatory risk. We have explicitly modeled market uncertainty, while regulatory risk - the possibility that the regulator committed to a price cap mechanism betrays expectations and changes the x factor because observed profits are very high - raises different issues. If revenues may be revised downwards because profits are “too high”, then the firm’s choices will be affected.

Panteghini and Scarpa (2003b) tackle the issue of whether the introduction of earnings sharing provisions solves this problem, with an investment of given size, showing how uncertainty which intervenes in good states of the world (the risk that high profits will be partially shared) does not affect investment decisions. In the framework we analyze here, it would be easy to show that the same conclusion applies to the initial (start-up) investment. However, regulatory risk may affect the size of total investment, and therefore the expansion decisions. Would earnings sharing be a good way to neutralize this effect? Every decision to expand the initial investment is taken looking at the future expected value of that expansion. At that moment, the logic governing the decision is the same as the one underlying the start-up. Therefore, regulatory risk linked to high profits does not modify the comparison between profit sharing and pure price cap that we have developed in the previous section.

Two-sided profit sharing. Many schemes with profit sharing do not only intervene when profits are too high, but when profits are low as well. In this way, the x factor can be adjusted downwards if demand or cost conditions worsen and profits fall below a given threshold. This would make "bad news" less "bad" and is therefore not neutral to investment decisions: this sort of insurance against market risks provides an additional incentive to invest. Therefore, Proposition 1 would be modified in that a two-sided earning sharing scheme encourages the firm to invest sooner than with a pure price cap. Expansion investments would equally be encouraged, so that the underinvestment result of Proposition 1 should be qualified: profit sharing leads to underinvestment (in the sense of Proposition 1) if it is one-sided, while the analysis with two-sided profit sharing would lead to a more ambiguous result.

The empirical analyses of the effects of earnings sharing schemes on investments do not yield clear-cut conclusions, and our results indicate good reasons why that may be so. However, there is room for further research. In particular some of the parameters of this model, such as the values of x factors, are set by the regulator. Thus an explicit framework taking into account the determination of these values would represent a valuable extension.

6 Appendix

In this Appendix we will prove our main results.

6.1 Derivation of (7)

Let's define the firm's revenues as $\Theta_t \equiv p_t q_t$. Using (2) and (6) we can derive the dynamics of revenues

$$d\Theta_t = \alpha_j \Theta_t dt + \sigma_q \Theta_t dz_t, \tag{18}$$

Given (18) and the definition of profit, the derivation of (7) is straightforward. It is worth noting that Θ_t represents the state variable of the investment problem. However, profit sharing intervenes whenever profits, rather than revenues, reach a threshold level $\widetilde{\Pi}$. To give readers a better intuition of results, we will thus express our findings in terms of the regulated state variable Π_t, rather than Θ_t. In particular, we will use the following switch level as

$$\widetilde{\Theta}(K) \equiv \tilde{\Pi}/\Psi(K). \tag{19}$$

The proofs will then be concluded by resetting results in terms of the regulated state variable Π.

6.2 Proof of Proposition 1

Let's apply dynamic programming to the firm's value (8). We can thus write

$$V(K,\Theta) = \Pi(K,\Theta)\,dt + e^{-rdt}E_0\left[V(K,\Theta + d\Theta)\right],$$

Expanding the right-hand side and using Itô's lemma we obtain

$$rV(K,\Theta) = \Pi(K,\Theta) + (r - \delta(x_l))\Theta V_\Theta(K,\Theta) + \frac{\sigma^2}{2}\Theta^2 V_{\Theta\Theta}(K,\Theta). \tag{20}$$

Differentiating (20) with respect to K, and defining $v(K,\Theta) \equiv V_K(K,\Theta)$, we obtain the following differential equation

$$rv(K,\Theta) = \Pi_K(K,\Theta) + (r - \delta(x_l))\Theta v_\Theta(K,\Theta) + \frac{\sigma^2}{2}\Theta^2 v_{\Theta\Theta}(K,\Theta), \tag{21}$$

which has the following closed-form solution

$$v(K,\Theta)=f(K,\Theta)+\sum_{i=1}^{2}a_i(K;x_l)\Theta^{\beta_i(x_l)}, \tag{22}$$

where $\beta_1(x_l)>1$ and $\beta_2(x_l)<0$ are the roots of the following characteristic equation:[19]

$$\frac{\sigma^2}{2}\beta(\beta-1)+(r-\delta(x_l))\beta-r=0.$$

The index l in $a_i(K;x_l)$ indicates that $x=x_l$, i.e. that profit sharing is not in place. The interpretation of equation (22) is then transparent. The contribution of the Kth unit of capital to the profit flow, when the existing stock of capital is K, is given by $\Pi_K(K,\Theta)\equiv\Psi_K(K)\Theta$, which is expected to grow at the rate α_l until the threshold $\tilde{\Pi}$ is reached, and at rate α_h afterwards. Thus, defining $\epsilon\equiv\frac{\delta(x_h)-\delta(x_l)}{\delta(x_l)\delta(x_h)}>0$ and $\widetilde{T}$ as the expected time of tightening regulation (i.e. when x rises to x_h), the expected present value of this contribution is

$$\begin{aligned}f(K,\Theta)&\equiv E_0\left[\int_0^{\widetilde{T}}e^{-rt}\Pi_K(K,\Theta;\alpha_l)\,dt+\int_{\widetilde{T}}^{\infty}e^{-rt}\Pi_K(K,\Theta;\alpha_h)\,dt\right]\\&=\frac{\Pi_K(K,\Theta)}{\delta(x_l)}-\epsilon\Pi_K(K,\tilde{\Theta})\left(\frac{\Pi(K,\Theta)}{\widetilde{\Pi}}\right)^{\beta_1(x_l)}.\end{aligned}$$

The boundary conditions for (22) are:[20]

$$\begin{aligned}v(K,\Theta^*)&=p_K, &(23)\\ v_\Theta(K,\Theta^*)&=0, &(24)\\ a_2(K,x_l)&=0, &(25)\\ a_1(\overline{K},x_l)&=0. &(26)\end{aligned}$$

As usual (23) and (24) are the VMC and SPC for the firm's optimal policy. Moreover, (25) imposes the irreversibility constraint on capital $dK\geq 0$.[21] The last condition (26) imposes $K\leq\overline{K}$.

[19] The roots are $\beta_{1,2}(x_l)=\frac{1}{2}-\frac{r-\delta(x_l)}{\sigma^2}\pm\sqrt{\left(\frac{1}{2}-\frac{r-\delta(x_l)}{\sigma^2}\right)^2+\frac{2r}{\sigma^2}}$ with $\frac{\partial\beta_1(x_l)}{\partial x_l}>0$.

[20] For further details on the boundary conditions see Dixit and Pindyck (1994, Ch. 6).

[21] In other words, when Θ is very small the expected present value of the last unit of capital installed is close to zero. Therefore, the value of the marginal option to scrap it is almost infinite.

Using (19), and substituting (22) into (23) and (24), we have

$$\frac{\Pi_K(K,\Theta^*)}{\delta(x_l)} - \epsilon\Psi_K(K)\widetilde{\Theta}(K)\left(\frac{\Pi(K,\Theta^*)}{\widetilde{\Pi}}\right)^{\beta_1(x_l)} + a_1(K;x_l)(\Theta^*)^{\beta_1(x_l)} = p_K,$$
$$\frac{\Pi_K(K,\Theta^*)}{\delta(x_l)} - \beta_1(x_l)\epsilon\Psi_K(K)\widetilde{\Theta}(K)\left(\frac{\Pi(K,\Theta^*)}{\widetilde{\Pi}}\right)^{\beta_1(x_l)} + \beta_1(x_l)a_1(K;x_l)(\Theta^*)^{\beta_1(x_l)} = 0.$$

Easy computations yield $\Theta^*_{PC}(K) \equiv \rho(x_l)\frac{p_K}{\Psi_K(K)}$ for $\Theta < \widetilde{\Theta}(K)$. Multiplying both sides by $\Psi(K)$ we thus obtain

$$\Pi^*(K) \equiv \Pi^*_{PC}(K) \equiv \rho(x_l)p_K\frac{\Psi(K)}{\Psi_K(K)} \quad \text{for } \Pi < \widetilde{\Pi}. \tag{27}$$

Since $\Psi_K(K)$ is decreasing in K, this identifies an upward-sloping curve. From conditions (23) and (24) we also obtain

$$\begin{aligned} a_1(K;x_l) = &-\left(\frac{\beta_1(x_l)-1}{p_K}\right)^{\beta_1(x_l)-1}\left(\frac{\Psi_K(K)}{\beta_1(x_l)\delta(x_l)}\right)^{\beta_1(x_l)} \\ &+\epsilon\Psi_K(K)\left(\frac{\Psi(K)}{\widetilde{\Pi}}\right)^{\beta_1(x_l)-1}. \end{aligned} \tag{28}$$

Finally, we need to show that the investment policy (27) is viable and optimal at $\tilde{\Pi}$. To do so, we define $\tilde{K}$ as the largest $K \leq \overline{K}$ that satisfies

$$\frac{\tilde{\Pi}}{\Psi(\tilde{K})} = \rho(x_l)\frac{p_K}{\Psi_K(\tilde{K})}$$

or multiplying both sides for $\Psi(\tilde{K})$,

$$\widetilde{\Pi} = \Pi^*_{PC}(\tilde{K}). \tag{29}$$

Given decreasing returns to scale, it is easy to show that $\tilde{K}$ exists and is unique. Furthermore, for all $K \leq \tilde{K}$ it turns out that $\Pi^*_{PC}(K) \leq \widetilde{\Pi}$ which concludes the first part of the proof.

Let us now turn to the case where $\tilde{K} \leq K \leq \overline{K}$. Notice that now it may well happen that, for given $K > \tilde{K}$, profit first goes beyond $\tilde{\Pi}$, while at a later stage $\Pi \leq \tilde{\Pi}$. In this case, in line with the spirit of the mechanism at stake, the price cap goes back to its original level. Recalling (8), the Bellman equations will be

$$\begin{aligned} &rV(K,\Theta) = \\ &= \Pi(K,\Theta) + (r-\delta(x_l))\Theta V_\Theta(K,\Theta) + \frac{\sigma^2}{2}\Theta^2 V_{\Theta\Theta}(K,\Theta) \\ &\text{for } \Pi \leq \widetilde{\Pi}, \end{aligned} \tag{30}$$

and

$$
\begin{aligned}
&rV(K,\Theta) = \\
&= \Pi(K,\Theta) + (r-\delta(x_h))\Theta V_\Theta(K,\Theta) + \tfrac{\sigma^2}{2}\Theta^2 V_{\Theta\Theta}(K,\Theta) \\
&\text{for } \Pi \geq \widetilde{\Pi}.
\end{aligned} \tag{31}
$$

Therefore, by the same line of reasoning, the contribution of the Kth unit of capital to the firm's value can be evaluated using (22)-(26) for $\Pi \leq \tilde{\Pi}$ with (27) as optimal policy. On the other hand, in the case $\Pi > \tilde{\Pi}$, it yields

$$
v(K,\Theta) = \frac{\Pi_K(K,\Theta)}{\delta(x_h)} + \sum_{i=1}^{2} a_i(K;x_h)\Theta^{\beta_i(x_h)}. \tag{32}
$$

where $\beta_1(x_h) > 1$ and $\beta_2(x_h) < 0$ are the roots of the following characteristic equation:[22]

$$
\frac{\sigma^2}{2}\beta(\beta-1) + (r-\delta(x_h))\beta - r = 0.
$$

The boundary conditions are

$$
\begin{aligned}
v(K,\Theta^*;\tilde{\Pi}) &= p_K && (33)\\
v_\Theta(K,\Theta^*;\tilde{\Pi}) &= 0 && (34)\\
a_2(K;x_h) &= 0 && (35)\\
a_1(\overline{K};x_h) &= 0 && (36)
\end{aligned}
$$

Again, easy computations yield the optimal policy as $\Theta^*_{PS}(K) \equiv \rho(x_h)\frac{p_K}{\Psi_K(K)}$, for $\Theta \leq \widetilde{\Theta}(K)$. Multiplying both sides by $\Psi(K)$ we obtain

$$
\Pi^*(K) \equiv \Pi^*_{PS}(K) \equiv \rho(x_h)p_K\frac{\Psi(K)}{\Psi_K(K)} \text{ for } \Pi \geq \widetilde{\Pi} \tag{37}
$$

while the integration constant is

$$
a_1(x_h,K) = -\left(\frac{\beta_1(x_h)-1}{p_K}\right)^{\beta_1(x_h)-1}\left(\frac{\Psi_K(K)}{\beta_1(x_h)\delta(x_h)}\right)^{\beta_1(x_h)} < 0. \tag{38}
$$

[22]The roots are $\beta_{1,2}(x_h) = \frac{1}{2} - \frac{r-\delta(x_h)}{\sigma^2} \pm \sqrt{\left(\frac{1}{2} - \frac{r-\delta(x_h)}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}}$.

To complete the proof we must now show that $\rho(x_l) < \rho(x_h)$ for $x_l < x_h$. Let's then differentiate $\beta_1(x_j)$ with respect to $\delta(x_j)$ with $j = l, h$, so as to obtain

$$\begin{aligned} \frac{\partial \beta_1(x_j)}{\partial \delta(x_j)} &= \frac{1}{\sigma^2}\left\{1 - \frac{\frac{r-\delta(x_j)}{\sigma^2} - \frac{1}{2}}{\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)}\right\} \\ &\equiv \frac{1}{\sigma^2}\frac{\beta_1(x_j) + \left(\frac{r-\delta(x_j)}{\sigma^2} - \frac{1}{2}\right) - \left(\frac{r-\delta(x_j)}{\sigma^2} - \frac{1}{2}\right)}{\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)} \\ &\equiv \frac{1}{\sigma^2}\frac{\beta_1(x_j)}{\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)}. \end{aligned}$$

Since

$$\frac{\partial}{\partial \beta_1(x_j)}\left(\frac{\beta_1(x_j)}{\beta_1(x_j) - 1}\right) = -\frac{1}{[\beta_1(x_j) - 1]^2} < 0,$$

we have

$$\begin{aligned} &\frac{\partial}{\partial \delta(x_j)}\left(\frac{\beta_1(x_j)}{\beta_1(x_j)-1}\delta(x_j)\right) = \\ &= \left[\frac{\partial}{\partial \beta_1(x_j)}\left(\frac{\beta_1(x_j)}{\beta_1(x_j)-1}\right)\right]\delta(x_j)\frac{\partial \beta_1(x_j)}{\partial \delta(x_j)} + \frac{\beta_1(x_j)}{\beta_1(x_j)-1} \\ &\equiv -\frac{\delta(x_j)}{[\beta_1(x_j)-1]^2}\frac{1}{\sigma^2}\frac{\beta_1(x_j)}{\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)} + \frac{\beta_1(x_j)}{\beta_1(x_j)-1} \\ &\equiv \frac{\beta_1(x_j)}{\beta_1(x_j)-1}\left\{1 - \frac{\delta(x_j)}{\sigma^2}\frac{1}{[\beta_1(x_j)-1]\left[\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)\right]}\right\} \\ &\equiv \frac{\beta_1(x_j)}{\beta_1(x_j)-1}\frac{f(\delta(x_j))}{[\beta_1(x_j)-1]\left[\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)\right]}, \end{aligned}$$

where

$$f(\delta(x_j)) \equiv [\beta_1(x_j) - 1]\left[\beta_1(x_j) - \left(\frac{1}{2} - \frac{r - \delta(x_j)}{\sigma^2}\right)\right] - \frac{\delta(x_j)}{\sigma^2}.$$

This implies that

$$\frac{\partial \rho(x_j)}{\partial \delta(x_j)} \propto f(\delta(x_j)). \tag{39}$$

Given (39) we must now prove that $f(\delta(x_j)) > 0$ for $\delta(x_j) \in (0, r]$. Let's first differentiate $f(\delta(x_j))$ with respect to $\delta(x_j)$. It is easy to have

$$\frac{\partial f(\delta(x_j))}{\partial \delta(x_j)} = \frac{\beta_1(x_j)}{\sigma^2}\frac{\beta_1(x_j) - 1}{\beta_1(x_j) - \left(\frac{1}{2} - \frac{r-\delta(x_j)}{\sigma^2}\right)} > 0, \text{ for } \delta(x_j) \in (0, r]. \tag{40}$$

Moreover it is easy to ascertain that

$$\begin{array}{c} \lim_{\delta(x_j)\to 0^+} f\left(\delta(x_j)\right) > 0, \\ f\left(r\right) > 0. \end{array} \tag{41}$$

Given (40) and (41) we can state that $f\left(\delta(x_j)\right) > 0$ and, hence, $\frac{\partial \rho(x_j)}{\partial \delta(x_j)} > 0$, for $\delta(x_j) \in (0, r]$. This means that, holding (39), we have $\rho(x_l) < \rho(x_h)$ for $x_l < x_h$. This concludes the proof.■

6.3 Proof of Lemma 1

To compute the firm's value let's start with the interval $K \geq \widetilde{K}$. Solving (31) for $\Pi \in (\widetilde{\Pi}, \Pi^*_{PS}(K))$ yields:

$$V\left(x_l, x_h; \widetilde{\Pi}\right) = \frac{\Pi\left(K, \Theta\right)}{\delta(x_h)} + \sum_{i=1}^{2} A_i(K; x_h)\Theta^{\beta_i(x_h)} \text{ for } \Pi \geq \widetilde{\Pi}. \tag{42}$$

In equation (42), the first term is the expected value of profit flows if K is held constant at its current level. The term $A_1(K; x_h)\Theta^{\beta_1(x_h)}$ measures the overall value of the firm's (call) options to expand and is thus positive. The term $A_2(K; x_h)\Theta^{\beta_2(x_h)}$ is the expected future gain due to looser regulation (with the switch from x_h to x_l) taking place whenever $\Pi < \widetilde{\Pi}$. For this reason $A_2(K, x_h)$ is positive as well.

Let's next focus on the region $\Pi(K, \Theta) \in (0, \widetilde{\Pi})$. Solving (30) yields

$$V\left(x_l, x_h; \widetilde{\Pi}\right) = \frac{\Pi\left(K, \Theta\right)}{\delta(x_l)} + \sum_{i=1}^{2} A_i(K; x_l)\Theta^{\beta_i(x_l)} \text{ for } \Pi \leq \widetilde{\Pi}. \tag{43}$$

To compute the value function, we use the boundary condition $V\left(K, 0\right) = 0$, which implies that $A_2(K; x_l) = 0$. The other term $A_1(K; x_l)\Theta^{\beta_1(x_l)}$ represents the consequences of reaching the profit sharing constraint in the future (from above) if the profit flow is reduced. This implies that $A_1(K; x_l)$ must be negative.

So far we have three constants $A_1(K; x_h)$, $A_2(K; x_h)$ and $A_1(K; x_l)$ to be determined. To this end, we assume that the value function is continuously differentiable at point $\widetilde{\Pi}$ where the two regimes meet

$$\begin{array}{c} \frac{\tilde{\Pi}}{\delta(x_h)} + \sum_{i=1}^{2} A_i(K; x_h)\tilde{\Theta}(K)^{\beta_i(x_h)} = \\ = \frac{\tilde{\Pi}}{\delta(x_l)} + A_1(K; x_l)(\tilde{\Theta}(K))^{\beta_1(x_l)}, \end{array} \tag{44}$$

$$\begin{aligned}&\tfrac{\tilde{\Pi}}{\delta(x_h)}+\textstyle\sum_{i=1}^{2}\beta_i(x_h)A_i(K;x_h)(\tilde{\Theta}(K))^{\beta_i(x_h)}=\\&=\tfrac{\tilde{\Pi}}{\delta(x_l)}+\beta_1(x_l)A_1(K;x_l)(\tilde{\Theta}(K))^{\beta_1(x_l)}.\end{aligned}\tag{45}$$

Finally, given (38), integrating $a_1(K;x_h)$ yields

$$\begin{aligned}A_1(K;x_h)&\equiv\int_K^{\overline{K}}-a_1(z;x_h)dz\\&=\left(\frac{\beta_1(x_h)-1}{p_K}\right)^{\beta_1(x_h)-1}\left(\frac{1}{\beta_1(x_h)\delta(x_h)}\right)^{\beta_1(x_h)}\int_K^{\overline{K}}(\Psi_K(z))^{\beta_1(x_h)}dz.\end{aligned}\tag{46}$$

Suppose now that $K\leq\tilde{K}$. In this case the profit sharing constraint is never binding and for the firm's value the only effective threshold is the investment policy $\Pi^*_{PC}(K)$.

For $\Pi\in(0,\Pi^*_{PC}(K))$, solving (20), the value function is:

$$V\left(x_l,x_h;\widetilde{\Pi}\right)=\frac{\Pi\left(K,\Theta\right)}{\delta(x_l)}+\sum_{i=1}^{2}A_i(K;x_l)\Theta^{\beta_i(x_l)}\text{ for }\Pi\in(0,\Pi^*_{PC}(K)).\tag{47}$$

Again, to compute (47) we use the boundary condition $V\left(K,0\right)=0$, which implies that $A_2(K;x_l)=0$. Unlike (43), the term $A_1(K;x_l)\Theta^{\beta_1(x_l)}$ represents the value of the firm's optimal future capacity expansion, in response to the evolution of Π towards the optimal investment policy $\Pi^*(K)$. Yet, unlike (42), here we should take into account the possible switches in the state variable Π.

Integrating (28) yields[23]

$$A_1(K;x_l)\equiv\int_{z=K}^{\overline{K}}-a_1(z;x_l)dz=A^{PC}(K;x_l)+A^{PS}(K;x_l,x_h),\tag{48}$$

where

$$A^{PC}(K;x_l)\equiv\left(\frac{\beta_1(x_l)-1}{p_K}\right)^{\beta_1(x_l)-1}\left(\frac{1}{\beta_1(x_l)\delta(x_l)}\right)^{\beta_1(x_l)}\int_{z=K}^{\overline{K}}(\Psi_K(z))^{\beta_1(x_l)}dz>0,$$

[23] *Note* that if $\tilde{K}=\overline{K}$ the constraint $\tilde{\Pi}$ disappears.

and

$$A^{PS}(K;x_l,x_h) \equiv -\epsilon \int_{z=K}^{\overline{K}} \Psi_K(z) \left(\frac{\Psi(z)}{\widetilde{\Pi}}\right)^{\beta_1(x_l)-1} dz \equiv -\epsilon c\left(\overline{K}\right) \widetilde{\Pi}^{1-\beta_1(x_l)} < 0.$$

where $\epsilon > 0$. This means that the introduction of a profit sharing threshold decreases the firm's value.

The comparison of (27) and (37) involves a change in the optimal policy during the period of optimization, i.e. there is a discontinuous jump in the optimal policy at $K = \widetilde{K}$. However, following Kamien and Schwartz (1991), we introduce a necessary condition at point $(\widetilde{K}, \Pi^*(\widetilde{K}))$, according to which the firm is indifferent between price cap and profit sharing, namely

$$\begin{aligned} &\tfrac{\Pi^*_{PC}(\widetilde{K})}{\delta(x_l)} + A_1(K,x_l)\left[\tfrac{\Pi^*_{PC}(\widetilde{K})}{\Psi(\widetilde{K})}\right]^{\beta_1(x_l)} = \\ &= \tfrac{\Pi^*_{PS}(\widetilde{K})}{\delta(x_h)} + \textstyle\sum_{i=1}^{2} A_i(K,x_h)\left[\tfrac{\Pi^*_{PS}(\widetilde{K})}{\Psi(\widetilde{K})}\right]^{\beta_1(x_h)}, \end{aligned} \tag{49}$$

where, using (27) and (37), we define $\Pi^*_{PC}(\widetilde{K})$ and $\Pi^*_{PS}(\widetilde{K})$ as the optimal policy immediately before and after tighter regulation. Condition (49) ensures that regime switches do not cause any discrete change in the firm's value. We thus obtain:

$$V^{PC}(x_l) = \frac{\Pi\left(K,\Theta\right)}{\delta(x_l)} + A^{PC}(K;x_l)\Theta^{\beta_1(x_l)},$$

and

$$\Delta V^{PS}(x_l,x_h;\widetilde{\Pi}) = A^{PS}(K;x_l,x_h)\Theta^{\beta_1(x_l)}.$$

The Lemma is thus proven.■

6.4 Proof of Lemma 2

Let's assume that a lower bound for quantity exists, defined as $\underline{q}$. The expected value of consumer surplus can be written as:

$$\begin{aligned} S(x_l,x_h;\widetilde{\Pi}) &= E_0\left[\textstyle\int_0^\infty \left(\int_{\underline{q}}^{q_t} p_t dq_t\right) e^{-rt}dt\right] - E_0\left[\textstyle\int_0^{\widetilde{T}} e^{-rt}p_tq_tdt + \int_{\widetilde{T}}^\infty e^{-rt}p_tq_tdt\right]. \\ &= E_0\left[\tfrac{\eta}{\eta-1}\textstyle\int_0^\infty e^{-rt}\left(\gamma_t\right)^{\frac{1}{\eta}}\left(q_t^{\frac{\eta-1}{\eta}} - \underline{q}^{\frac{\eta-1}{\eta}}\right)dt\right] - E_0\left[\textstyle\int_0^{\widetilde{T}} e^{-rt}p_tq_tdt + \int_{\widetilde{T}}^\infty e^{-rt}p_tq_tdt\right] \end{aligned}$$

Recalling that $\Theta_t \equiv p_t q_t = (\gamma_t)^{\frac{1}{\eta}} q_t^{\frac{\eta-1}{\eta}}$,we get:

$$\begin{array}{l} S(x_l, x_h; \widetilde{\Pi}) = \frac{\eta}{\eta-1}\left\{E_0\left[\int_0^\infty e^{-rt}\Theta_t dt\right] - E_0\left[\int_0^\infty e^{-rt}(\gamma_t)^{\frac{1}{\eta}} \underline{q}^{\frac{\eta-1}{\eta}} dt\right]\right\} + \\ -E_0\left[\int_0^{\widetilde{T}} e^{-rt}\Theta_t dt + \int_{\widetilde{T}}^\infty e^{-rt}\Theta_t dt\right] = \\ = \frac{\eta}{\eta-1}\left\{E_0\left[\int_0^\infty e^{-rt}\Theta_t dt\right] - E_0\left[\int_0^\infty e^{-rt}(\gamma_t)^{\frac{1}{\eta}} \underline{q}^{\frac{\eta-1}{\eta}} dt\right]\right\} + \\ -E_0\left[\int_0^\infty e^{-rt}\Theta_t dt + e^{-r\widetilde{T}}[\frac{\tilde{\Theta}}{\delta(x_h)} - \frac{\tilde{\Theta}}{\delta(x_l)}]\right], \end{array} \tag{50}$$

Therefore, (50) can be rewritten as

$$\begin{aligned} S(x_l, x_h; \widetilde{\Pi}) &= \frac{1}{\eta-1} E_0\left[\int_0^\infty e^{-rt}\Theta_t dt\right] - \frac{\eta}{\eta-1} E_0\left[\int_0^\infty e^{-rt}(\gamma_t)^{\frac{1}{\eta}} \underline{q}^{\frac{\eta-1}{\eta}} dt\right] \\ &\quad + e^{-r\widetilde{T}}[\frac{\tilde{\Theta}}{\delta(x_h)} - \frac{\tilde{\Theta}}{\delta(x_l)}] \\ &= S^{PC}(x_l) + \Delta S^{PS}(x_l, x_h; \widetilde{\Pi}), \end{aligned} \tag{51}$$

where $S^{PC}(x_l) \equiv \frac{1}{\eta-1}\frac{\Theta}{\delta(x_l)} - \frac{\eta}{\eta-1}\frac{pq}{r}$ is the consumer surplus under price cap regulation and $\Delta S^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv B^{PS}(x_l, x_h; \widetilde{\Pi})\Theta^{\beta_1(x_l)}$, with $B^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv \epsilon\left(\frac{\widetilde{\Pi}}{\Psi(K)}\right)^{1-\beta_1(x_l)}$, is the expected increase in the consumer surplus once profit sharing becomes stringent. Thus we obtain (13).

6.5 Proof of Proposition 2

Using (47), (48), and (51), we obtain (11) in the text, where $W^{PC} \equiv S^{PC} + \lambda V^{PC}$ is the welfare function under price-cap regulation and the second term is given by

$$\begin{array}{c} \Delta W^{PS}(x_l, x_h; \widetilde{\Pi}) \equiv \Delta S^{PS}(x_l, x_h; \widetilde{\Pi}) + \lambda \Delta V^{PS}(x_l, x_h; \widetilde{\Pi}) \\ = \epsilon\left(\tilde{\Pi}\right)^{1-\beta_1(x_l)}\left\{\Psi(\tilde{K})^{\beta_1(x_l)-1} - \lambda\int_{z=K}^{\overline{K}} \Psi_K(z)\left(\Psi(z)\right)^{\beta_1(x_l)-1} dz\right\}\Theta^{\beta_1(x_l)}. \end{array} \tag{52}$$

Using (52) we easily obtain (15).■

6.6 Proof of Proposition 3

Let us recall (15) and compute

$$\max_{\widetilde{\Pi}} \Delta W^{PS}(x_l, x_h; \widetilde{\Pi}) = \max_{\widetilde{\Pi}} \epsilon \widetilde{\Pi}^{1-\beta_1(x_l)} \left[\Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-1} - \lambda c\left(\overline{K}\right)\right] \Theta^{\beta_1(x_l)}. \tag{53}$$

The first order condition is

$$\begin{aligned} \frac{\partial \Delta W^{PS}(x_l, x_h; \widetilde{\Pi})}{\partial \widetilde{\Pi}} &= \epsilon \left[1 - \beta_1(x_l)\right] \widetilde{\Pi}^{-\beta_1(x_l)} \left[\Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-1} - \lambda c\left(\overline{K}\right)\right] + \\ &+ \epsilon \widetilde{\Pi}^{1-\beta_1(x_l)} \left[\beta_1(x_l) - 1\right] \Psi_K\left(\widetilde{K}\right) \Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-2} \frac{\partial \widetilde{K}(\widetilde{\Pi})}{\partial \widetilde{\Pi}} = 0. \end{aligned} \tag{54}$$

Using (54) we obtain

$$\begin{aligned} \frac{\partial \Delta W^{PS}(x_l, x_h; \widetilde{\Pi})}{\partial \widetilde{\Pi}} &= \epsilon \left[\beta_1(x_l) - 1\right] \widetilde{\Pi}^{-\beta_1(x_l)} \left\{ \lambda c\left(\overline{K}\right) + \right. \\ & \left. - \Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-1} \left[1 - \frac{\widetilde{\Pi} \Psi_K\left(\widetilde{K}\left(\widetilde{\Pi}\right)\right)}{\Psi\left(\widetilde{K}\left(\widetilde{\Pi}\right)\right)} \frac{\partial \widetilde{K}\left(\widetilde{\Pi}\right)}{\partial \widetilde{\Pi}} \right] \right\}. \end{aligned} \tag{55a}$$

Recall that $\widetilde{K}$ is such that

$$\rho(x_l)\, p_K \frac{\Psi\left(\widetilde{K}\right)}{\Psi_K\left(\widetilde{K}\right)} = \widetilde{\Pi}. \tag{56}$$

Rewriting (56) as

$$\rho(x_l)\, p_K = \frac{\Psi_K\left(\widetilde{K}\right) \widetilde{\Pi}}{\Psi\left(\widetilde{K}\right)} \tag{57}$$

and differentiating (57) yields

$$\frac{\partial \widetilde{K}}{\partial \widetilde{\Pi}} = \left[\frac{\beta_1(x_l)}{\beta_1(x_l) - 1} \delta(x_l)\, p_K \right]^{-1} \left\{ 1 - \frac{\Psi\left(\widetilde{K}\right) \Psi_{KK}\left(\widetilde{K}\right)}{\left[\Psi_K\left(\widetilde{K}\right)\right]^2} \right\}^{-1}. \tag{58}$$

Given $\Psi(K) = K^{\varepsilon}$ with $\varepsilon \in (0,1)$ we have $\Psi_K(K) < \frac{\Psi(K)}{K}$ for any K. Therefore, we can write

$$1 - \frac{\Psi\left(\widetilde{K}\right)\Psi_{KK}\left(\widetilde{K}\right)}{\left[\Psi_K\left(\widetilde{K}\right)\right]^2} = \frac{1}{\varepsilon}.$$

Next, substituting (57) and (58) into (55a) we easily obtain

$$\frac{\partial \Delta W^{PS}(x_l, x_h; \widetilde{\Pi})}{\partial \widetilde{\Pi}} = \epsilon\left[\beta_1(x_l) - 1\right]\widetilde{\Pi}^{-\beta_1(x_l)}\left\{\lambda c\left(\overline{K}\right) - (1-\varepsilon)\Psi\left(\widetilde{K}\right)^{\beta_1(x_l)-1}\right\}. \tag{59}$$

Using (59), and applying the Envelope Theorem, the second order condition holds, i.e.:

$$\frac{\partial^2 \Delta W^{PS}(x_l, x_h; \widetilde{\Pi})}{\left(\partial\widetilde{\Pi}\right)^2} \propto -\left\{(1-\varepsilon)\left[\beta_1(x_l) - 1\right]\Psi\left(\widetilde{K}\right)^{-1}\Psi_K\left(\widetilde{K}\right)\frac{\partial \widetilde{K}}{\partial \widetilde{\Pi}}\right\} < 0$$

Solving (59) yields

$$\left[\frac{\lambda c\left(\overline{K}\right)}{1-\varepsilon}\right]^{\frac{1}{\varepsilon[\beta_1(x_l)-1]}} = \widetilde{K}. \tag{60}$$

and since $\underline{K}$ is nil we get:

$$c\left(\overline{K}\right) = \int_0^{\overline{K}} \Psi_K(z)\left(\Psi(z)\right)^{\beta_1(x_l)-1} dz = \frac{\Psi\left(\overline{K}\right)^{\beta_1(x_l)}}{\beta_1(x_l)}. \tag{61}$$

Substituting (60) into (61) it is straightforward to show that if $\varepsilon < 1 - \frac{\lambda}{\beta_1(x_l)}$, the inequality $\widetilde{K} < \overline{K}$ always holds. Finally, using (56) and (60), we obtain (17).■

6.7 Comparative statics

Recall that $\frac{\partial \beta_1(x_l)}{\partial \sigma} < 0$[24] and that, by assumption, $\Psi\left(\overline{K}\right) \leq 1$. This implies that $\overline{K}^{\varepsilon} \leq 1$ and, hence, $\overline{K} \leq 1$. Using (16), and computing partial derivatives of MS and MC, we have:

[24] See Dixit and Pindyck (1994).

σ	$\frac{\partial MS}{\partial \sigma} = \varepsilon MS \underbrace{\log \overline{K}}_{\leq 0} \cdot \underbrace{\frac{\partial \beta_1(x_l)}{\partial \sigma}}_{<0} > 0$	$\frac{\partial MC}{\partial \sigma} = MC \cdot$ $\cdot \underbrace{\left(\varepsilon \log \overline{K} - \frac{1}{\beta_1(x_l)}\right)}_{<0} \cdot \underbrace{\frac{\partial \beta_1(x_l)}{\partial \sigma}}_{<0} > 0$
λ	$\frac{\partial MS}{\partial \lambda} = 0$	$\frac{\partial MC}{\partial \lambda} = c\left(\overline{K}\right) > 0$
$\overline{K}$	$\frac{\partial MS}{\partial \overline{K}} = 0$	$\frac{\partial MC}{\partial \overline{K}} = \frac{\varepsilon \beta_1(x_l) MC}{\overline{K}} > 0$
ε	$\frac{\partial MS}{\partial \varepsilon} =$ $= \left(-\frac{1}{1-\varepsilon} + (\beta_1(x_l) - 1) \underbrace{\log \widetilde{K}}_{\leq 0}\right) < 0$	$\frac{\partial MC}{\partial \varepsilon} = \beta_1(x_l)\, MC \cdot \underbrace{\log \overline{K}}_{\leq 0} \leq 0$

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