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Irreversible investments and regulatory risk*

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Abstract

This paper addresses the issue of how regulatory constraints affect firm's investment choices when the firm has an option to delay investment. The $RPI - x$ rule is compared to a profit sharing rule, which increases the x factor in case profits go beyond a given level. It is shown that a pure price cap and profit sharing are identical in their impact on investment choices: the change in the option value that we have with a profit sharing regime exactly compensates the change in the "direct" profitability of investment. Regulatory risk - breaching of the regulatory contract - may or may not affect negatively investment decisions. Even if a distortion exists, we show that this distortion is the same, even if a pure price cap could be considered riskier than a profit sharing rule.

JEL Classification: L51, D92, G31
Keywords: regulation, investment, RPI-x, profit sharing.

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1 Introduction

The theoretical literature and the practical experience on regulated industries try to identify the optimal price scheme, able to strike a balance between the pursuit of allocative efficiency (keeping prices in line with marginal costs), the need to provide an incentive to invest (which is sometimes referred to as "dynamic" efficiency) and the political necessity to take particular care of consumer's welfare (sometimes called "distributional" efficiency). While there is a general tendency to shift from a regulation of the rate of return to a scheme which looks for "efficient" prices, there is little agreement on the optimal pricing scheme. A price cap such as the by now traditional $RPI - x$ seems to provide a reasonable compromise, in that real prices decrease over time while the regulated firm seems to have appropriate incentives to invest[1].

However, we know from the UK experience that an $RPI - x$ scheme tends to leave the firm large profits. This means that regulators may be subject to considerable political pressures to adjust prices even before the scheduled time (the price review). This has happened for instance in 1995, when the UK electricity regulator - realising that its previous intervention on prices had been too mild - intervened on prices well before the price review, which was due in 1999. Other times, the same type of concern has lead to direct political interventions. This happened for instance when a "windfall tax" on profits was introduced in Britain with the 1997 budget, affecting 33 privatised utilities, whose profits had been considered excessively high.

These possibilities entail a specific type of policy uncertainty for utilities, sometimes called "regulatory risk". The effect of this risk is documented, for instance, by Buckland and Fraser (2001), who indicate that it reverberates into the cost of capital of regulated utilities. As a possible remedy to this problem, an alternative called "sliding scale" (or, less cryptically, "profit sharing") has been considered[2]. According to this scheme, if the firm's profits

[1] The idea is that for long periods of time (regulatory periods, which end with a price review), the regulated price should increase at a rate equal to the difference between the expected inflation rate (the Retail Price Index, RPI) and an exogenously given component (x) which, roughly speaking, represents the expected increase of productivity the firm should attain. By making prices - at least within these periods - insensitive at the margin to firm's choices, the $RPI - x$ rule appears to eliminate the downward bias and the phenomenon known as "underinvestment". As Beesley and Littlechild (1989) put it when listing the main arguments in favor of $RPI - x$, "Because the company has the right to keep whatever profits it can earn during the specified period (and must also absorb any losses), this preserves the incentive to productive efficiency associated with unconstrained profit maximization".

[2] Among others, Sappington and Weisman, (1996) and Burns *et al.* (1998). This proposal, already debated in the UK, has also become popular among several policy makers,

go beyond a pre-specified level, the x factor should be automatically adjusted upwards, making the price cap more stringent; this re-distributes rents to the consumers, making the system more "fair" and more sustainable from a political viewpoint. The idea is that when this automatic mechanism is in place there is no need for discretionary interventions, as excess profits automatically trigger a tighter regulatory constraint.

However, this proposal has been criticized by some authors (see e.g., Mayer and Vickers, 1996) who - among other things - stress that if investments spur profits and therefore trigger a tighter price cap, then we have a dis-incentive to invest. The superiority of the $RPI - x$ system relative to profit sharing rules on the ground of technical efficiency was recognized also by advocates of profit sharing rules (e.g., Lyon, 1996), who only defend the PS system on the basis of overall allocative efficiency (profit sharing "typically" increases consumers surplus). Weisman (1993) shows that when price cap rules incorporate an element of profit sharing, price caps may represent a worsening relative to a pure cost based regulation (a notoriously inefficient set-up). Notice however that in practice the evidence in favour of pure price cap schemes is extremely weak; for instance, Ai and Sappington (2002) show extremely mixed results in the case of the US telecoms.

This paper tackles the issue of possible investment distortions induced by regulatory constraints and regulatory risk. While most papers in the regulation literature (e.g., Laffont and Tirole, 1986) implicitly consider fully reversible investments, we take a different approach which, following the modern theory of investment, stresses how these choices are typically *irreversible.* However, firms usually can choose the optimal timing of investment as well. This implies that they are endowed with an option to delay.

Our study shows that considering this aspect considerably changes the relative desirability of the aforementioned regulatory policies. Using a continuous time model, we show that the effect of $RPI - x$ and profit sharing on the incentives to invest are identical. The reason is that the introduction of the profit ceiling into a $RPI - x$ scheme decreases the net present value of the investment, but also decreases the value of waiting (i.e., the option value) by exactly the same amount. This is an application of the "bad news principle" (Bernanke, 1983), which indicates that, under investment irreversibility, uncertainty acts asymmetrically since only the unfavorable events affect the current propensity to invest. If, thus, profit sharing (i.e., the change in the x factor) occurs only in the good state, investment decisions are not affected[3].

We then consider how policy uncertainty changes this result, showing

such as the Italian electricity regulator.

[3] In Panteghini and Scarpa (2003) we use a simple two-period model to show this first result and the distributional effectiveness of this mechanism. This is in line with the

that the argument according to which profit sharing - by reducing the risk of regulatory interventions due to excessive profits - encourages investment is not correct. If regulatory "surprises" are linked to profits, profit sharing is irrelevant because it protects the firm when the firm does not need to be protected, namely when profits are high. If the firm knows that the tightening of the cap may occur only in case of "good news" (high profits), its investment decisions will not be affected by this type of risk. If profit sharing has a justification, this lies in distributional considerations, not in efficiency ones.

For instance, one of the regulators' main targets is the rent extraction *per se*. As we have shown in Panteghini and Scarpa (2003) profit sharing has a greater ability to raise rents than price cap, and it is possible to extract the *same* amount of rents with a *lower* value of x_l. Given the amount of rents extracted from the monopolist, under profit sharing the trigger point above which investment is profitable is thus lower than under a pure price cap; in other words, investment is undertaken earlier than under the pure price cap regime.

This paper is linked to three streams of literature. The first one is the literature on investment irreversibility. Irreversibility may arise from 'lemon effects' (second-hand capital goods may be impossible to sell), and from capital specificity (see Dixit and Pindyck, 1994, and Trigeorgis, 1996)[4]. The irreversibility of capital expenditures is even more obvious in markets subject to price regulation, which are typically natural monopolies; the scarcity (or total absence) of firms operating in the same sector and the public constraints coming from nature of the service may represent decisive factors in this respect[5]. Relative to this literature, we consider how investment is affected by different regulatory rules, showing how the option value of irreversible investments matters in determining the optimal regulatory policy.

The second stream of literature is the one on regulation and investment. From Laffont and Tirole (1986), we know that optimal price schemes entail a distortion in firms' (reversible) investment choices. The rule labelled "$RPI - x$" (Beesley and Littlechild, 1989) was introduced exactly to counter this

finding of Dixit (1991) within a perfectly competitive set-up.

[4] Irreversibility may be caused by industry comovements as well: when a firm wants to resell its capital because of negative market conditions, but potential buyers operating in the same industry are subject to the same conditions, the firm may have to sell the capital at a lower price than otherwise possible.

[5] An idea of the empirical relevance of irreversible investments in regulated industries can be obtained looking at the so called "stranded costs", i.e., at the value of assets that following liberalisation will hardly find a remuneration, but cannot be shifted to a different productive use. According to Lyon and Mayo (2000) these costs can be estimated for the US electricity sector "in the neighborhood of $200 billion".

problem. In this case, investment does not affect price, so that this rule is supposed to have "minimum" distortionary effects on investment choices. In our paper we consider the option value of an investment of a given amount, to see how different regulatory schemes affect the timing of investment and whether regulatory risk is a good reason to introduce profit sharing. Our first result is that profit sharing does not underperform the purest version of $RPI - x$[6]. However, a second result is that profit sharing does not "beat" a pure price cap scheme in terms of ability to deal with regulatory risk. The two systems seem equivalent in these respects.

Finally, an established literature indicates that political risk may have a negative impact on the firms' propensity to undertake irreversible investment, and some recent contributions [see e.g. Altug *et al.* (2000), (2001)] have analyzed the issue with irreversibility, where the results are less clear-cut. This is in general correct, and we confirm this result in our framework. However, our main focus is to check whether the difference between the alternative regulatory regimes we consider makes a difference in this respect, and in section 3 we show that in general the introduction of profit sharing does not reduce the impact of uncertainty on investment.

The paper is organized as follows. The next section provides the analytical set-up in continuous time, stressing how profit sharing does not reduce the incentive to invest relative to a pure price cap scheme when lump-sum irreversible investments are considered. Section 3 considers regulatory risk, showing another neutrality result: profit sharing - even if it eliminates part of regulatory risk - does not outperform a pure price cap. Section 4 concludes the paper and discusses possible extensions.

2 The model

In this section we introduce a simple continuous-time infinite horizon model describing the behavior of a firm. The market is characterized by the demand function $q(t) = q(p(t))$, where p and q are price and quantity of the good at time t. Production takes place at a per-period cost given by $C = c(t)q(t)$. Furthermore, in order to obtain the profit $\Pi(t)$, the firm needs to build an infrastructure:

[6] This result can be usefully linked to some recent results of the empirical literature. For instance, Crew and Kleindorfer (1996) and the papers they review stress how the presumed superiority of optimal price rules does not emerge so clearly from experiences in different countries and sectors. The claim that $RPI - x$ rules lead to more efficient investment patterns than profit related regulatory schemes does not find a clear empirical support.

- **Assumption 1** (investment). Production requires a one-off investment of a given amount I.

This could be the case, for instance, of an energy distributor that has to decide whether or not to invest in a new network (either a pipeline or wires) in order to serve a town. A relevant aspect of this assumption is that the amount of investments is given[7]. Although firms often have the possibility to marginally adjust the value of their expenditures, it is also true that the size of most investment projects that utilities face is by and large determined by the size of the area they want to serve. Building a new electric line connecting two nodes of a transmission system to improve its reliability, or a pipeline to sell gas to a new city are choices that entail an expenditure that can only partially be controlled by the firm. This type of major investments is what we focus on.

In these cases the firm is left with two major choices: *whether* or not to undertake the investment, and *when* to do so. Therefore, while the notion of "underinvestment" typically refers to the amount spent by the firm, in this context we will talk of underinvestment referring to the probability that a firm invests and to the date of the investment, i.e. to the *expected present* value of the investment. The apparent difference between our notion and the usual one is simply due to the fact that we explicitly model uncertainty and time.

If the firm does not undertake the investment, its profit is normalised to zero. From the moment in which the firm invests, its per-period profits are[8]

$$\Pi(t) = m(t)p(t)q(t) \tag{1}$$

where $m(t)$ is the mark up.

- **Assumption 2** The mark up evolves according to the following

  $$dm(t) = \alpha_m m(t)dt \tag{2}$$

  where the parameter α_m captures the idea that (nominal) cost changes over time[9].

[7]See the final section for the consequences of relaxing this assumption.

[8]As we look at the consequences of different regulatory schemes on a firm's decisions, information on costs is assumed to be symmetric. The choice of the optimal price should instead consider asymmetric information, but this is beyond the scope of the current work.

[9]This may be due to external factors affecting technology and input prices. Notice that mark up $m(t)$ might also be thought of as a function of some endogenous input ν as well. In this way we could introduce into the model the idea that the firm might choose a reversible input (e.g., effort) to minimize its current costs. Formally this would mean that we would have $m(t) = \max_\nu m(\nu; t)$. The quality of the results would remain unchanged (Dixit and Pindyck, 1994, cap.10).

Demand is stochastic, and we introduce the following

- **Assumption 3**. Demand follows a geometric Brownian motion

$$dq(t) = \alpha_q q(t)dt + \sigma q(t)dz_q \tag{3}$$

where α_q and σ are the growth rate and variance parameter, respectively.

Price is determined by the regulator in a way we will define in the next sections.

The firm has an infinite time horizon and maximizes the (discounted) present value of future expected profit.

2.1 Pure price cap

We will first assume that price regulation follows the traditional price-cap rule known as $RPI - x$ (Beesley and Littlechild, 1989).

Definition 1 *(*Price Cap*) Under the Price Cap $RPI - x$ rule, if the firm starts producing at time t^*, the initial price p_0 is given, and its dynamics are defined by the difference between the inflation rate (changes in the retail price index, RPI) and an exogenous factor x_l:*

$$p(t) = p_0 e^{(RPI - x_l)t} \tag{4}$$

for $t \geq t^*$.

The factor $x = x_l$ is linked to the productivity gain (cost reduction) that the regulator expects the firm to be capable of achieving every year, but is determined at the beginning and is thus exogenous to the firm. As already stressed, the logic of the $RPI - x$ rule is that, by making prices insensitive at the margin to firm's choices, it appears to eliminate underinvestment. Also notice that here we assume that price dynamics is given over an infinite horizon, so that current investments have no impact on prices either in the short- or in the long-run.

Using equations (1), (2), (3) and (4) and applying Itô's lemma we can obtain the profits' dynamics

$$d\Pi(t) = \alpha\Pi(t)dt + \sigma\Pi(t)dz \tag{5}$$

where $\alpha \equiv RPI - x_l + \gamma + \alpha_q + \alpha_m$ is the expected growth rate of per-period profits. Given the dividend rate δ (which must be positive in order for the net value of the firm to be bounded) and the risk-free interest rate r, we must have $r - \delta = \alpha$[10]. Solving for the dividend rate we thus obtain

$$\delta(x) = r - (RPI - x_l + \gamma + \alpha_q + \alpha_m)\,. \tag{6}$$

The firm must solve a standard optimal stopping time problem, namely it must choose the timing of investment to maximize the expected present value of its payoff. The problem can be represented as follows

$$\max_t E\left[(V_{PC}(\Pi(t)) - I)e^{-rt}\right] \tag{7}$$

where $E\,[.]$ denotes the expectation operator, $V_{PC}(\Pi(t))$ is the project value under the price cap, i.e. the NPV of the project at time t. The solution of the problem (7), i.e. the optimal time of investments, will be defined as t^*.

Using dynamic programming, the firm's value $V_{PC}(\Pi(t))$ can be written as

$$V_{PC}(\Pi(t)) = \Pi(t)dt + e^{-rdt}E\left[V_{PC}(\Pi(t) + d\Pi(t))\right]$$

Expanding the right-hand side and using Itô's lemma one obtains

$$rV_{PC}(\Pi(t)) = \Pi(t) + (r - \delta(x))\Pi V_{PC_\Pi}(\Pi(t)) + \frac{\sigma^2}{2}\Pi^2 V_{PC_{\Pi\Pi}}(\Pi(t)) \tag{8}$$

where $V_{PC_\Pi} = \partial V_{PC}/\partial\Pi(t)$ and $V_{PC_{\Pi\Pi}} = \partial^2 V_{PC}/\partial\Pi^2(t)$, respectively. For simplicity, hereafter, we will omit the time variable t.

To compute the value function, it is assumed that $V_{PC}(0, x) = 0$, namely when Π is very small, the project is almost worthless, and that no speculative bubbles exist[11]. Thus, equation (8) has the following solution

$$V_{PC}(\Pi, x) = \frac{\Pi}{\delta(x_l)}. \tag{9}$$

As shown by Dixit and Pindyck (1994), the option function has the following form

$$O_{PC}(\Pi, x) = A\Pi^{\beta_1(x_l)} \tag{10}$$

[10] As shown in Panteghini and Scarpa (2001) considering shareholders' risk aversion does not change the result.

[11] See Dixit and Pindyck (1994, Ch. 5 and 6).

where A is a parameter to be determined, and $\beta_1(x_l)$ is the positive root of the following characteristic equation[12]

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

The optimal investment timing can be computed using the Value Matching Condition (VMC) and the Smooth Pasting Condition (SPC). Given the regulatory regime i (i.e. either price cap or profit sharing), the former condition requires the net present value of the project to be equal to the option value to defer investment, $O_i(\Pi, x)$, namely

$$V_i(\Pi, x_l)-I=O_i(\Pi, x_l) \text{ with } i=PC, PS. \tag{VMC}$$

The second condition requires the slopes of the functions $[V_i(\Pi, x_l)-I]$ and $O_i(\Pi, x)$ to match

$$\frac{\partial\left[V_i(\Pi, x_l)-I\right]}{\partial\Pi}=\frac{\partial O_i(\Pi, x_l)}{\partial\Pi} \text{ with } i=PC, PS. \tag{SPC}$$

Conditions VMC and SPC characterize optimal time t^*. Notice that, given (5), this value can be associated to a profit level Π^*: whenever current profit reaches Π^*, the firm invests.

To solve the optimal stopping time problem, let us substitute (9) and (10) into the VMC and the SPC. We thus obtain a two-equation system with two unknowns: the trigger point of Π, above which investment is profitable, and the coefficient A. It is easy to show that the trigger point is[13]

$$\Pi^*_{PC}(x_l)\equiv\frac{\beta_1(x_l)}{\beta_1(x_l)-1}\delta(x_l)I \tag{11}$$

[12] The positive root is

$$\beta_1(x_l)=\frac{1}{2}-\frac{r-\delta(x_l)}{\sigma^2}+\sqrt{\left(\frac{r-\delta(x_l)}{\sigma^2}-\frac{1}{2}\right)^2+\frac{2r}{\sigma^2}}.$$

It is easy to ascertain that $\frac{\partial\beta_1(x_l)}{\partial x_l}>0$.

[13] Substituting $\Pi^*_{PC}(x_l)$ into the system one easily obtains

$$A=\frac{I}{\beta_1(x_l)-1}\left(\Pi^*_{PC}(x_l)\right)^{-\beta_1(x_l)}>0.$$

The option value multiple in equation (11), $\frac{\beta_1(x)}{\beta_1(x)-1} > 1$, shows that the gross present value

$$V_{PC}^*(\Pi_{PC}^*(x_l), x_l) \equiv \frac{\Pi_{PC}^*(x_l)}{\delta(x_l)} = \frac{\beta_1(x_l)}{\beta_1(x_l)-1} I$$

must exceed the investment cost I to compensate for irreversibility. It is straightforward to show that an increase in x_l decreases both the expected profit V_{PC}^* and the opportunity cost of investing O_{PC}^*. As shown by Moretto, Panteghini and Scarpa (2003), however, we have:

Remark 1 *An increase in* x_l *increases* $\Pi_{PC}^*(x_l)$ *(i.e.,* $\frac{\partial \Pi_{PC}^*(x_l)}{\partial x_l} > 0$*).*

This implies that having a $RPI - x$ reduces the incentive to invest. Therefore, the $RPI - x$ rule is not neutral to investment decisions, a claim possibly implicit in Beesley and Littlechild (1989) but explicit in much of the policy debate.

Remark 2 *We can label the above result "underinvestment" in that, given initial price and a distribution of cost parameters, the* present expected *value of investment is reduced because of the price cap rule.*

2.2 Profit sharing

The $RPI - x$ rule has been criticised on the ground that cost decreases are often more substantial than predicted, and this leaves the firm most of the increase in surplus which follows privatisation.

To tackle this fairness concern in a predictable way, an alternative to $RPI - x$ has been proposed, called profit sharing[14]. This scheme is defined as follows:

Definition 2 *(*Profit sharing*) Under the profit sharing regulatory mechanism, the* $RPI - x$ *rule remains in place as long as profit remains below an exogenous level* $\widetilde{\Pi}$. *If* $\Pi(t) > \widetilde{\Pi}$, *the* x *factor immediately*[15] *increases to* $x_h > x_l$*:*

$$p(t) = \begin{cases} p_0 e^{(RPI - x_l)t} & \text{if } \Pi(t) \leq \widetilde{\Pi} \\ \\ p_0 e^{(RPI - x_h)t} & \text{if } \Pi(t) > \widetilde{\Pi}, \text{ with } x_h > x_l \end{cases} \tag{PS}$$

[14] Notice that one could also have an intervention rule based on the level of revenues instead of profits; see Sappington and Weisman (1996).

[15] In a discrete-time framework it would be sensible to introduce a delay between the observation of a profit level and the adjustment of the x factor. In this set-up this would introduce a very substantial analytical complication with no relevant change in the results.

Thus, the price decrease factor remains constant as long as profit is considered "reasonable". When they become "excessive", this mechanism redistributes part of the surplus to the consumers[16]. In this section we analyze this issue.

If $\Pi < \widetilde{\Pi}$ the Brownian motion is the same as in the previous section. Notice that it is natural to assume that the $\widetilde{\Pi}$ is above the trigger point. Otherwise, the price scheme would start from a value of x already equal to x_h. This would obviously contradict the definition of profit sharing, i.e. the idea that regulation starts with a given value x_l, which is made *more* stringent at a *later* stage, in case profit goes beyond a certain level.

In this case, the Brownian motion describing the regulated payoff is

$$d\Pi = \begin{cases} \alpha\Pi dt + \sigma\Pi dz & \text{if } \Pi(t) \leq \widetilde{\Pi} \\ \\ \alpha'\Pi dt + \sigma\Pi dz & \text{if } \Pi(t) > \widetilde{\Pi} \end{cases} \tag{12}$$

with $\alpha' \equiv RPI - x_h + \gamma + \alpha_q + \alpha_m < \alpha$. If $\Pi > \widetilde{\Pi}$, therefore, the dividend rate is given by equality $r - \delta(x_h) = \alpha'$, which implies the inequalities $\delta(x_h) > \delta(x_l) > \delta$. When a switch point $\widetilde{\Pi}$ is introduced, both the option function and the value function must be solved separately for $\Pi < \widetilde{\Pi}$ and $\Pi > \widetilde{\Pi}$. Then, the values and derivatives of the functions are equated at the switch point $\Pi = \widetilde{\Pi}$ (see Dixit and Pindyck, 1994, pp. 186-189).

Notice that it may well happen that profit first goes beyond $\widetilde{\Pi}$, while at a later stage $\Pi < \widetilde{\Pi}$. In this case - in line with the spirit of the mechanism at stake - our formulation guarantees that the price cap goes back to its original level.

In order to check whether an investment project is profitable, both explicit and opportunity costs must be taken into account. Thus, investment is profitable if (*and when*) the present discounted value of future profits, net of both costs, is positive.

Following the same procedure as above, we start with the analysis of the value function. The general solution is given by the sum of a perpetual rent, with discount rate $\delta(x_h)$, and a homogeneous (exponential) part. Again, it is assumed that $V_{PS}(0, x_l, x_h) = 0$ and that no speculative bubbles exist. Thus

[16] It would be possible to extend the current analysis to a case where different switch points ($\widetilde{\Pi}_1$, $\widetilde{\Pi}_2$,...) and increasing values of the x factor are introduced (the equivalent of a progressive taxation). Moreover, the case in which price dynamics may be adjusted downwards if profits are too low might be a straightforward extension. We will return later on this point.

the solution of the value function is

$$V_{PS}(\Pi, x_l, x_h) = \begin{cases} \frac{\Pi}{\delta(x_l)} + V_1 \Pi^{\beta_1(x_l)} & \text{if} \quad \Pi < \widetilde{\Pi}, \\ \\ \frac{\Pi}{\delta(x_h)} + V_2 \Pi^{\beta_2(x_h)} & \text{if} \quad \Pi > \widetilde{\Pi}. \end{cases} \tag{13}$$

As shown in Panteghini and Scarpa (2001), equating the two components of (13) at the switch point $\Pi = \widetilde{\Pi}$ and considering the SPC one obtains parameters V_1 and V_2. Both parameters depend on the regulatory coefficients x_l and x_h. In particular, $V_1 \Pi^{\beta_1(x_l)} < 0$: this represents the present value of future profit changes due to the profit sharing (when Π goes beyond $\widetilde{\Pi}$). $V_2 \Pi^{\beta_2(x_h)} > 0$ measures the present value of the future increase in the profit participation when Π goes below $\widetilde{\Pi}$ (in fact $\partial \Pi^{\beta_2(x_h)} / \partial \Pi < 0$).

Let us now turn to the option value, $O_{PS}(\Pi, x_l, x_h)$. In the $(0, \widetilde{\Pi})$ region, condition $O_{PS}(0, x_l, x_h) = 0$ holds, and, therefore, the value function has the standard form $C_1 \Pi^{\beta_1(x_l)}$.

In the $(\widetilde{\Pi}, \infty)$ region, instead, the option function is given by the sum of $B_1 \Pi^{\beta_1(x_h)}$ and $B_2 \Pi^{\beta_2(x_h)}$ (with B_1 and B_2 to be determined). $\beta_1(x_h)$ and $\beta_2(x_h)$ are the roots of the characteristic equation $\frac{\sigma^2}{2}\beta(\beta - 1) + (r - \delta(x_h))\beta - r = 0$, with $\beta_1(x_h) > 1$ and $\beta_2(x_h) < 0$[17]. To sum up, the option function is

$$O_{PS}(\Pi, x_l, x_h) = \begin{cases} C_1 \Pi^{\beta_1(x_l)} & \text{if} \quad \Pi < \widetilde{\Pi}, \\ \\ B_1 \Pi^{\beta_1(x_h)} + B_2 \Pi^{\beta_2(x_h)} & \text{if} \quad \Pi > \widetilde{\Pi}. \end{cases} \tag{14}$$

By equating the values and the derivatives of the two components of the option function at point $\Pi = \widetilde{\Pi}$, we can compute B_1 and B_2 as functions of C_1. As shown in Panteghini and Scarpa (2001), $B_1 \propto C_1$ and $B_2 \propto C_1$.

Substituting equations (14) and (13) into the VMC and SPC one obtains the trigger point and the unknown parameter C_1 of the option function. In the $(0, \widetilde{\Pi})$ region, these conditions lead to the following system

$$\begin{aligned} \frac{\Pi}{\delta(x_l)} + V_1 \Pi^{\beta_1(x_l)} - I &= C_1 \Pi^{\beta_1(x_l)} \\ \frac{1}{\delta(x_l)} + V_1 \beta_1(x_l) \Pi^{\beta_1(x_l)-1} &= C_1 \beta_1(x_l) \Pi^{\beta_1(x_l)-1} \end{aligned} \tag{15}$$

[17] The roots are

$$\beta_{1,2}(x_h) = \frac{1}{2} - \frac{r - \delta(x_h)}{\sigma^2} \pm \sqrt{\left(\frac{r - \delta(x_h)}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}},$$

and it is easy to ascertain that, given derivative $\frac{\partial \beta_1(x)}{\partial x} > 0$, inequality $\beta_1(x_h) > \beta_1(x_l)$ holds.

which yields the same trigger point as the one obtained under the pure price cap system in equation (11)[18]

$$\Pi^*_{PS}(x_l) \equiv \frac{\beta_1(x_l)}{\beta_1(x_l) - 1}\delta(x_l)I, \tag{16}$$

The equality between $\Pi^*_{PS}(x_l)$ and $\Pi^*_{PC}(x_l)$ establishes the following:

Proposition 1 *(*Neutrality of profit sharing*) Consider a regulated monopolist which has to decide on an irreversible investment of a given amount. When demand is uncertain as modelled in (3) and the timing of investment is endogenous, correcting the $RPI - x$ rule with a profit sharing element does not affect the timing of investment.*

The neutrality (indifference) result can be explained as follows.

Since the tightening of the price cap takes place only in case of "good news", the bad news principle implies that, while profit sharing actually reduces the firm's rents, it does not interfere with its decision to invest relative to the pure price cap rule. There are no investment projects that will be undertaken under one regime, but not under the other.

The intuition for this result can be obtained considering how the option value of investment changes the firm's problem. Relative to the case of pure price cap, profit sharing reduces the *net* value of the project and its option value *by the same amount*. What matters to the decision to invest is whether or not the return from the project is positive, not "by how much"; given that profit sharing intervenes *only in case* profits become large enough to anyway justify the investment, this feature does not affect the firm's decision.

Another way to look at the issue is to stress that profit sharing is equivalent to equity participation by the consumers. Recall, in fact, that when $\Pi > \widetilde{\Pi}$, a given part of the surplus is redistributed to the consumers. When instead $\Pi < \widetilde{\Pi}$, consumers do not share the bad result. We can thus say that the profit sharing device is equivalent to a case where consumers are endowed with a put option with strike price $\widetilde{\Pi}$, written on the firm's profits. If, therefore, the firm's return drops below $\widetilde{\Pi}$ (bad result), consumers sell their equity participation at zero price. Then, they will re-buy (at zero price) their participation when the firm faces a good result, namely when $\Pi > \widetilde{\Pi}$.

[18]It is easy to show that

$$C_1 = \frac{\beta_2(x_h) - 1}{\beta_1(x_l) - \beta_2(x_h)} \frac{\delta(x_h) - \delta(x_l)}{\delta(x_h)\delta(x_l)} \widetilde{\Pi}^{1-\beta_1(x_l)} + \frac{1}{\beta_1(x_l)} \frac{\Pi^*_{PS}(x_l)^{1-\beta_1(x_l)}}{\delta(x_l)} > 0.$$

To clarify this point, let us concentrate on the $(0, \widetilde{\Pi})$ region (with $\Pi^*_{PS}(x_l) < \widetilde{\Pi}$). Recall equations (13), (14), and the solution of C_1. The negative term $V_1\Pi^{\beta_1(x)}$ measures the value of the consumers' put option, which must be added to both the project value and the option function. This addition is necessary because, irrespective of whether the firm is waiting or producing, a worthy put option is owned by the consumers. Since $V_1\Pi^{\beta_1(x)}$ enters both functions, the difference $[V_{PS}(\Pi, x_l, x_h) - O_{PS}(\Pi, x_l, x_h)]$ is independent of the switch level $\widetilde{\Pi}$, thereby making the profit-sharing device neutral.

Easy computations show that, for a given payoff, the higher the switch point the greater the value of V_1. This implies that $\frac{\partial C_1}{\partial \widetilde{\Pi}} = \frac{\partial V_1}{\partial \widetilde{\Pi}} > 0$. Therefore, a change in $\widetilde{\Pi}$ affects both the value and the option function by the same amount. Finally, note that the higher the switch point $\widetilde{\Pi}$ the lower the put option value ($-V_1\Pi^{\beta_1(x_h)}$). Of course, for $\widetilde{\Pi} \to \infty$, profit sharing vanishes, and the value of the put option turns out to be nil.

3 Regulatory risk

In this section we qualify the previous neutrality result by introducing regulatory risk[19]. Indeed, price cap schemes are intrinsically risky for the firm, as they promise a fixed pricing rule for considerable time periods. Any policy of this kind is subject to the credibility critique: fixing price can be time-inconsistent. In particular, in order to induce the firm to invest the regulator may announce a rate of price decrease (x_l), but may change it later. More in general, the regulator may announce a policy which "guarantees" the firm a certain profitability, and then revise this policy in various ways[20]. The Windfall Tax introduced in Britain in 1997 and the regulated prices freeze introduced in Italy in 2002 are examples of this phenomenon. The firm will anticipate this risk and revise its investment plans accordingly. Buckland and Fraser (2001) document this fact, showing that regulatory changes are reflected by an increase in the Beta of electricity distributors in the UK, evidence that systematic political and regulatory risks are indeed present.

If we consider actual regulatory policies in the past few years, we can see that policy uncertainty (or regulatory risk) may originate from two kinds of concerns. First of all, "policy makers"[21] could decide to cut prices for reasons

[19] In discussing tax neutrality, Sandmo (1979, p.176) argues that "academic discussions of tax reform in a world of unchanging tax rates is something of a contradiction in terms". This point well applies to regulation as well.

[20] Aubert and Laffont (2002) raise a similar point from a different viewpoint, analysing elements who may lead to a renegotiation of the regulatory contract.

[21] We shall not distinguish between regulators and "politicians". Even if in principle the

such as inflationary concern, greater attention for low income consumers, or other reasons not directly related to a direct dissatisfaction with the outcome of the regulatory policy *per se*. These interventions typically interfere with the price mechanism and decrease the firm's profitability, even if the firm's profits are not the direct *cause* of the intervention. In other cases, policy makers may be concerned that the distribution of welfare is "unfair" in some sense, i.e. that the regulated firm is enjoying most of the benefits from the regulatory regime, while consumers keep paying high prices. In this latter case, the policy change is due to a variable which is determined *endogenously* in our model, i.e. profit.

In our set-up, we show that regulatory risk may or may not matter, depending on which of the above factors are at stake. To this end, it will prove useful to distinguish two types of risk. The first one is "pure" regulatory risk; by this, we mean that a positive probability exists, that Government changes, sudden inflationary concerns or other reasons external to the regulated market induce the regulator to tighten the price cap. Therefore, the possible change in the x factor is not linked to any variable pertaining to the description of this market environment. The second one is profit-related risk, namely the possibility that an increase in profits might trigger an unexpected tightening of regulatory constraints.

3.1 Regulatory risk and investment decisions

Let us start from the effects of uncertainty on the basic value of the x factor, x_l. In doing so we follow Dixit's (1991) suggestion to explore the effects of regulatory uncertainty by introducing a Poisson process. On this point, we can obtain our first result[22].

Proposition 2 *If, under either a price cap or a profit sharing regime, there is uncertainty about the value of the x_l factor as*

$$dx_l = \begin{cases} 0 & \textit{with probability} \quad 1-\lambda dt, \\ \Delta x_l \neq 0 & \textit{with probability} \quad \lambda dt, \end{cases} \tag{17}$$

areas of competence of regulators and those of Governments are distinct, in practice this is not always the case, and it is not always relevant to the firm. On the first point, regulators are sensitive to political pressures and at times are *de facto* overruled by political bodies. On the second one, both regulatory interventions and legal "reforms" are able to affect firm's profitability. Given that what matters is the regulated firm's reaction, distinguishing the source of this uncertainty does not seem too relevant to our analysis.

[22] This is also in line with some influential articles in the taxation literature, such as Cummins *et. al.* (1996) and Hassett *et al.* (1994).

where $\Delta x_l \equiv x_{l,1} - x_{l,0}$, *with* $x_{l,1}$ *and* $x_{l,0}$ *representing the price cap factor after and before the change, respectively, investment is affected by policy uncertainty. In particular, we find that:*

a) if $x_{l,0} > x_{l,1}$, *an increase in* λ *encourages investment (i.e. reduces the trigger point);*

b) if $x_{l,0} < x_{l,1}$, *the effect of an increase in* λ *is ambiguous;*

c) the effect is the same irrespective of the regime applied.

Proof: See the Appendix.

A change in the value of x_l affects investment. If there exists some probability that regulation gets *less* tight in the future, regulatory uncertanty encourages investment. The reason is that a less demanding regulatory constraint increases the NPV of the investment, and this unambiguously makes investment more desirable. In particular, notice that x_l intervenes both in the case of good news and in the case of bad news and anything that makes "bad news" less negative encourages investment.

If there exists some probability that regulation gets tighter, the effect is ambiguous. This ambiguity is caused by the different effect of regulatory uncertainty on the value function and the option function. On the one hand, the expected increase in the x factor reduces the firm's profitability, thereby discouraging investment. On the other hand, the firm might anticipate investment to exploit the lower current x factor. These counteracting effects lead to an ambiguous result.

Finally, whatever the effect of this uncertainty on investment, adding a profit sharing component to the price cap does not make a difference. Notice that with profit sharing the factor x_l is relevant only before the profit sharing threshold is reached. In this region $\left(\Pi \in \left[0, \widetilde{\Pi}\right]\right)$ profit sharing does not matter. This explains point c) of Proposition 2.

Let us now consider the uncertainty that might be present even under profit sharing[23], regarding the value x_h and/or on the threshold level $\widetilde{\Pi}$. We can prove that this additional element of uncertainty does not affect a firm's investment choices.

Proposition 3 *Assume that, under profit sharing, the rate* x_h *and the value of* $\widetilde{\Pi}$ *follow Poisson processes*

$$dx_h = \begin{cases} 0 & \textit{with probability} \quad 1 - \lambda dt, \\ \Delta x_h & \textit{with probability} \quad \lambda dt, \end{cases}$$

[23] Notice that usually profit sharing elements are introduced exactly to reduce regulatory risk. As profit sharing entails an automatic correction in case firm's profits are "too large", regulators are better able to resist political pressures to intervene and to breach the regulatory contract.

$$d\widetilde{\Pi} = \begin{cases} 0 & \textit{with probability} \quad 1-\lambda dt, \\ \Delta\widetilde{\Pi} & \textit{with probability} \quad \lambda dt, \end{cases}$$

where $\Delta x_h \equiv x_{h,0} - x_{h,1}$ *and* $\Delta\widetilde{\Pi} \equiv \widetilde{\Pi}_0 - \widetilde{\Pi}_1$ *with* $x_{h,i}$ *and* $\widetilde{\Pi}_i$ *represent the parameter values at state* i*. On condition that* $\min(\widetilde{\Pi}_0, \widetilde{\Pi}_1) > \Pi^*_{PC}(x_l)$*, these sources of uncertainty do not affect investment.*

P roof. See Appendix. ■

The intuition for these results is straightforward, in line with the discussion of the above Proposition 2: events affecting the firm's profitability when $\Pi > \widetilde{\Pi}$ are irrelevant to investment decisions.

Finally, we can consider a case where uncertainty affects the base rate (x_l) but conditional on the profit level: here the regulatory risk affects price regulation *only* after a certain (high) profit level. In order to analyze the issue, we model this "risk of expropriation" under pure price cap as follows:

$$p(t) = \begin{cases} p_0 e^{(RPI-x_l)t} & \text{if } \Pi(t) \leq \Pi' \\ \\ p_0 e^{(RPI-x_l)t} & \text{if } \Pi(t) > \Pi' \text{, with probability} \quad 1-\lambda dt \\ p_0 e^{(RPI-x_h)t} & \text{if } \Pi(t) > \Pi' \text{, with probability} \quad \lambda dt \end{cases} \tag{18}$$

with Π' exogenous. In other terms, we assume that there is a positive probability - modelled as a Poisson variable - that if the profit level is "excessive" the policy maker will intervene, making regulation tighter ($x_h > x_l$) in order to redistribute part of the rents to the consumers. Notice that - in line with our definition of profit sharing - we assume that in case the profit level falls below Π' the value of the x factor returns with probability 1 to its original level, x_l. For the sake of simplicity, we are also assuming that Π' is known and given, and the same applies to x_h.

Proposition 4 *As long as* $\Pi' > \Pi^*_{PC}(x_l)$*, policy uncertainty as modelled in (18) does not affect the investment decision.*

The above Proposition is almost a corollary to Proposition 3. Given that uncertainty on the x factor intervenes only for high profit levels, investment is not affected.

3.2 Discussion of the results

In order to discuss these results, we return to our previous definitions of "pure regulatory risk" and of "risk of rent expropriation".

The first one (totally exogenous risk) is what we have modelled in Propositions 2 and 3. These results show that uncertainty on the "base" value of the x factor - the one that applies as soon as the firm operates - matters to the firm's decision. Firms may postpone or anticipate investment decisions because of policy uncertainty. Part c) of Proposition 2 is more interesting, showing that the effect of this exogenous policy uncertainty is the same, independently of the regulatory mechanism in place. This uncertainty may regard an x factor which does not depend on the profit level, or may affect the value of x which is supposed to change in case profits go beyond a given and known profit level - as with profit sharing, the case considered in Proposition 3; however, this does not make a difference. What matters is that the relevant x factor in place was not supposed to increase in the way described by (17).

Therefore, the two regimes are equivalent when the firm faces this type of exogenous uncertainty.

The second type of regulatory risk is sometimes labelled risk of expropriation (Vickers, 1993): in this case, policy changes are related to "excessive" profit levels [see (18)]. Notice that the profit sharing scheme is usually introduced exactly in order to have *automatic* corrections if the regulated firm's profits are excessively high, making unanticipated interventions "unnecessary".

Proposition 3 indicates that profit sharing actually neutralises the regulatory risk linked to the possibility of rent expropriation. However, the relevant point is: does a pure price cap suffer this risk? If the answer were positive, then we could conclude that profit sharing actually represents an improvement relative to a pure price cap. However, the answer - somehow surprisingly - is negative. Proposition 4 indicates that this type of risk will not interefere with investment decisions even when the regulatory regime is a pure price cap. This may be seen as a consequence of the bad news principle, which tells us that what happens in case of good news (i.e., when the profit level is higher than the one at which the firm decides to start the project) does not affect the firm's decision.

Notice that this has a relevant implication. The typical justification for profit sharing is that regulatory authorities are unable to commit not to intervene if the regulated firm's profits turn out to be very high: firms may fear that, if profits are "too high" the regulator might intervene, tightening the price cap scheme. This source of uncertainty is probably eliminated if the regulatory scheme envisages an *automatic* intervention (increasing the x factor from x_l to x_h). Any political pressure to expropriate the firm could find an answer in this device, thereby decreasing the incentive for the regulator to surprise the firm, and increasing the firm's incentive to invest. Our result indicates that this typical argument in favour of profit sharing is flawed: uncertainty on the level of profit after which the price cap will become tighter is irrelevant.

4 Conclusions and extensions

Relative to the existing literature, which implicitly assumed reversible investment by regulated firms, our results appear significantly different. While the current literature indicates that profit sharing has a negative effect on investment decisions, our paper shows that this is not necessarily the case. What makes a difference is the introduction of two fairly realistic assumptions: investment irreversibility and the firm's ability to decide when to invest. This implies that the firm is endowed with a call option to delay the investment, which expires when investment is undertaken. We have thus shown that a profit sharing device reduces both the value of the project and the value of the option to wait by the same amount. According to the Bad News Principle, therefore, no additional distortion is introduced, with respect to price cap.

We have then analysed whether profit sharing is a good device to foster investment by reducing a firm's uncertainty on future regulatory policies. However, we have shown that profit sharing is ineffective to this end. In a pure price cap scheme, the possibility that the regulator might intervene to tighten the price cap factor if profits are high is not relevant to investment decisions. This is because this regulatory intervention would take place in case profits are high, i.e. in the case of "good" news. This is simply a consequence of the Bad News Principle: like any other source of uncertainty, political uncertainty taking place "in case of high profits" does not affect investment timing.

At least two immediate extensions of the present framework are possible, and we would like to illustrate them in sequence, to show whether and to what extent they would modify our result.

The first one is about *two sided profit sharing***.** In many cases, profit sharing schemes are "two sided", meaning that the x factor changes upwards when profit is too large, but is also revised (downwards) if profit is too low. In this way, the regulatory scheme provides a form of insurance to the firm, in that a decrease in profits is partially compensated by the reduction in the x factor. If a scheme is two sided, then Proposition 1 changes, in that the PS does not only intervene in case of good news, but in the case of bad news as well. As a reduction in x would make bad news "less bad", this type of profit sharing would actually *encourage* investment relative to the case of a pure price cap: two sided profit sharing is more conducive to investment than a pure price cap.

A second extension may regard *cost reducing investments*. The investment we have formally considered is one, which increases profits. Although in our framework the investment is necessary for the firm to have a revenue (the expansion is from zero to the current level given by (1)) the result clearly holds whether or not the initial revenue level is zero. However, it is easy to ascertain that the same analysis applies, if one interprets the investment as a cost-reducing one. All the conditions relevant to our results refer to profit levels and profit dynamics. Whether these dynamics are due to revenue expansion rather than to cost reduction, is totally irrelevant. The crucial difference between our conclusions and those usually obtained (e.g., Laffont and Tirole, 1986) lies in the irreversibility of the investment we consider. The traditional underinvestment result is perfectly valid for reversible investments (e.g., managerial effort - which is indeed the explicit focus of the traditional analyses), while our analysis shows that they should be interpreted with great care when investments are irreversible.

Finally, the assumption that investment size is given may be considered a limitation, and in Moretto, Panteghini and Scarpa (2003) - which does not consider regulatory risk - we have analysed in detail what happens when we remove it. In that paper we consider an investment which consists of an initial, start-up capacity and possible future expansions. The comparison between price cap and profit sharing indicates that profit sharing is irrelevant to the start-up decision (in full analogy with the result of Proposition 1 in this paper). However, only when the firm reaches the stock of capital at which PS intervenes, further incremental investments will be delayed; hence, some underinvestment becomes possible for high levels of capital.

If one considers our previous results, it is clear that, as long as invested capital is not too large, price cap and profit sharing remain equivalent in their effects, and our previous propositions apply with no change. For higher profit levels - and larger investments - the ability of profit sharing to deal with regulatory risk remains an open issue, that we would like to analyse in further work.

5 Appendix

This Appendix contains the proofs of Propositions 2 and 3.

5.0.1 Proof of Proposition 2

Define $V_{j,i}(\Pi)$ as the value function under the scheme $j = PC, PS$, either before the change ($i = 0$) or after it ($i = 1$).

We will focus on the $\left(0, \widetilde{\Pi}\right)$ region in either case. Under the pure price cap regime, by definition, we have $\widetilde{\Pi} \to \infty$. Under profit sharing, it is natural to assume that $\widetilde{\Pi}$ is above the trigger point.

Let us then compute the closed-form solutions of the value function under the new regime ($i = 1$). The solution obtained is equal to that computed in the absence of policy risk. Using dynamic programming, the firm's value $V_{j,1}(\Pi)$ can be written as

$$V_{j,1}(\Pi) = \Pi dt + e^{-rdt} E\left[V_{j,1}(\Pi + d\Pi)\right].$$

Expanding the right-hand side and using Itô's lemma one obtains

$$rV_{j,1}(\Pi) = \Pi + (r - \delta(x_{l,1}))\Pi \frac{\partial V_{j,1}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2 \frac{\partial^2 V_{j,1}(\Pi)}{\partial \Pi^2}. \tag{19}$$

Let the boundary condition $V_{j,1}(0) = 0$ hold. Thus the solution of (19) is

$$V_{j,1}(\Pi, x_{l,1}) = \frac{\Pi}{\delta(x_{l,1})} + L_1^j \Pi^{\beta_1(x_{l,1})} \text{ for } \Pi \in \left(0, \widetilde{\Pi}\right), \tag{20}$$

where $\beta_1(x_{l,1})$ is the positive root of the characteristic equation[24]

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

Under the assumption that no bubbles exist, as $\widetilde{\Pi} \to \infty$, L_1^j goes to 0. This entails that, under the pure price cap scheme, the firm's value reduces to a perpetual rent $\frac{\Pi}{\delta(x_{l,1})}$. Under profit sharing, instead, $L_1^j \neq 0$, since the firm's value must account for the switch in the x-factor which takes place whenever $\Pi > \widetilde{\Pi}$.

Let us next compute the option function

$$O_{j,1}(\Pi) = e^{-rdt} E\left[O_{j,1}(\Pi + d\Pi)\right]$$

[24]The positive root is

$$\beta_1(x_{l,1}) = \frac{1}{2} - \frac{r - \delta(x_{l,1})}{\sigma^2} + \sqrt{\left(\frac{r - \delta(x_{l,1})}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}}.$$

Expanding the right-hand side and using Itô's lemma one obtains

$$rO_{j,1}(\Pi) = [r - \delta(x_{l,1})]\, \Pi \frac{\partial O_{j,1}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2 \frac{\partial^2 O_{j,1}(\Pi)}{\partial \Pi^2} \tag{21}$$

which yields

$$O_{j,1}(\Pi) = A_1^j \Pi^{\beta_1(x_{l,1})} \tag{22}$$

where A_1^j is a parameter to be determined. Using the VMC and SPC, we thus obtain the trigger point

$$\Pi_j^*(x_{l,1}) \equiv \Pi^*(x_{l,1}) \equiv \frac{\beta_1(x_{l,1})}{\beta_1(x_{l,1}) - 1}\delta(x_{l,1})I \tag{23}$$

and

$$A_1^j - L_1^j = \frac{I}{\beta_1(x_{l,1}) - 1}\left[\Pi^*(x_{l,1})\right]^{-\beta_1(x_{l,1})}.$$

Notice that under profit sharing (i.e. $L_1^j \neq 0$), the values of A_1^j and L_1^j can be computed by stitching together the two branches of the value function at point $\Pi = \widetilde{\Pi}$. However, their computation is not relevant for our purposes.

Let us now turn to the pre-change value function. Write the firm's value as

$$V_{j,0}(\Pi) = \Pi dt + (1 - \lambda dt)e^{-rdt}E\left[V_{j,0}(\Pi + d\Pi)\right] + \lambda dt e^{-rdt}E\left[V_{j,1}(\Pi + d\Pi)\right].$$

Expanding the right-hand side and using Itô's lemma one obtains

$$(r + \lambda)V_{j,0}(\Pi)) = \Pi + (r - \delta(x_{l,0}))\Pi\frac{\partial V_{j,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 V_{j,0}(\Pi)}{\partial \Pi^2} + \lambda V_{j,1}(\Pi) \tag{24}$$

Substituting (20) into (24) one obtains

$$(r + \lambda)V_{j,0}(\Pi) = \frac{\delta(x_{l,1}) + \lambda}{\delta(x_{l,1})}\Pi + \lambda L_1^j \Pi^{\beta_1(x_{l,1})} + (r - \delta(x_{l,1}))\Pi\frac{\partial V_{j,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 V_{j,0}(\Pi)}{\partial \Pi^2}.$$

It is easy to ascertain that the general solution of $V_{j,0}(\Pi)$ is

$$V_{j,0}(\Pi) = H_0\Pi + G_0\lambda L_1^j \Pi^{\beta_1(x_{l,1})} + \sum_{i=1}^{2} H_i^j \Pi^{\beta_i(x_{l0})},$$

where

$$H_0 \equiv \frac{\delta(x_{l,1}) + \lambda}{\delta(x_{l,0}) + \lambda} \frac{1}{\delta(x_{l,1})},$$

$$G_0 \equiv \frac{1}{r + \lambda - \beta_1(x_{l,1}) \left\{ [r - \delta(x_{l,1})] + [\beta_1(x_{l,1}) - 1] \frac{\sigma^2}{2} \right\}},$$

and where $\beta_i(x_{l,0})$ are the roots of the characteristic equation[25]

$$\frac{\sigma^2}{2} \beta(\beta - 1) + (r - \delta(x_{l,0}))\beta - (r + \lambda) = 0.$$

It is worth noting that G_0 must be positive in order for a solution to be obtained. Let the boundary condition $V_{j,0}(0) = 0$ hold. This implies that $H_2^j = 0$.

Notice that, under profit sharing, $H_1^{PS} \neq 0$, since the firm's value must account for the switch in the x-factor which takes place whenever $\Pi > \widetilde{\Pi}$. Under the pure price cap scheme, instead, we have $H_1^{PC} = 0$, on condition that no bubbles exist. The computation of H_1^{PS} can be obtained by letting the branches of the pre-change value function meet at point $\Pi = \widetilde{\Pi}$. However, this computation is not relevant for our purposes.

Given the above conditions, the closed-form solution reduces to

$$V_{j,0}(\Pi) = H_0 \Pi + G_0 \lambda L_1^j \Pi^{\beta_1(x_{l,1})} + H_1^j \Pi^{\beta_1(x_{l,0})}. \tag{25}$$

Following the same procedure, we can compute the option function. Start with the Bellman equation

$$O_{j,0}(\Pi) = (1 - \lambda dt) e^{-rdt} E\left[O_{j,0}(\Pi + d\Pi)\right] + \lambda dt e^{-rdt} E\left[O_{j,1}(\Pi + d\Pi)\right].$$

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

$$(r + \lambda) O_{j,0}(\Pi) = (r - \delta(x_{l,0}))\Pi \frac{\partial O_{j,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2} \Pi^2 \frac{\partial^2 O_{j,0}(\Pi)(\Pi)}{\partial \Pi^2} + \lambda O_{j,1}(\Pi). \tag{26}$$

[25] The positive root is

$$\beta_1(x_{l,0}) = \frac{1}{2} - \frac{r - \delta(x_{l,0})}{\sigma^2} + \sqrt{\left(\frac{r - \delta(x_{l,0})}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2\,(r + \lambda)}{\sigma^2}}.$$

Substituting (22) into (26) yields

$$(r+\lambda)O_{j,0}(\Pi) = \lambda A_1^j \Pi^{\beta_1(x_{l,1})} + (r-\delta(x_{l,1}))\Pi \frac{\partial O_{j,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2 \frac{\partial^2 O_{j,0}(\Pi)}{\partial \Pi^2}$$

The general solution of $O_{j,0}(\Pi)$ is

$$O_{j,0}(\Pi) = G_0 \lambda A_1^j \Pi^{\beta_1(x_{l,1})} + \sum_{i=1}^{2} G_i^j \Pi^{\beta_i(x_{l,0})}$$

Using the boundary condition $O_{j,0}(0) = 0$, we have $G_2^j = 0$. Thus, we obtain

$$O_{j,0}(\Pi) = G_0 \lambda A_1^j \Pi^{\beta_1(x_{l,1})} + G_1^j \Pi^{\beta_1(x_{l,0})} \tag{27}$$

Let us now compute the trigger point above which investment is profitable under policy risk. Substituting (25) and (27) into the VMC and SPC, we obtain a two-equation system

$$\begin{aligned} &H_0\Pi + G_0\lambda\left(L_1^j - A_1^j\right)\Pi^{\beta_1(x_{l,1})} + \left(H_1^j - G_1^j\right)\Pi^{\beta_1(x_{l,0})} - I = 0 \\ &H_0 - \beta_1(x_{l,1})G_0\lambda\left(L_1^j - A_1^j\right)\Pi^{\beta_1(x_{l,1})-1} + \beta_1(x_{l,0})\left(H_1^j - G_1^j\right)\Pi^{\beta_1(x_{l,0})-1} = 0 \end{aligned}$$

with two unknowns, i.e. the difference $\left(H_1^j - G_1^j\right)$ and the trigger point $\Pi^*(x_{0,1})$. Simplifying yields

$$\frac{\beta_1(x_{l,0})-1}{\beta_1(x_{l,0})} H_0 \Pi_u + \left(1 - \frac{\beta_1(x_{l,1})}{\beta_1(x_{l,0})}\right) G_0 \lambda \left(L_1^j - A_1^j\right) \Pi_u^{\beta_1(x_{l,1})} = I, \tag{28}$$

where Π_u is the trigger point under policy uncertainty.

Let us next rewrite (28) as

$$\frac{\Pi_u}{\Pi^*(x_{l,0})} = \left[\frac{\delta(x_{l,0}) + \lambda\, \delta(x_{l,1})}{\delta(x_{l,1}) + \lambda\, \delta(x_{l,0})}\right] \left[\frac{I - \left(1 - \frac{\beta_1(x_{l,1})}{\beta_1(x_{l,0})}\right) G_0 \lambda \left(L_1^j - A_1^j\right) \Pi^{\beta_1(x_{l,1})}}{I}\right].$$

where $\Pi^*(x_{l,0}) \equiv \frac{\beta_1(x_{l,0})}{\beta_1(x_{l,0})-1}\delta(x_{l,0})I$ is the trigger point in the absence of policy uncertainty when $x = x_{l,0}$.

If $x_{l,0} > x_{l,1}$ we have $\frac{\delta(x_{l,0})+\lambda\, \delta(x_{l,1})}{\delta(x_{l,1})+\lambda\, \delta(x_{l,0})} < 1$. Moreover, the term $\left(1 - \frac{\beta_1(x_{l,1})}{\beta_1(x_{l,0})}\right)$ is positive: this entails that the second term in squared brackets on the RHS is less than 1, as well. Therefore the inequality $\Pi_u < \Pi^*(x_{l,0})$ holds. This proves point a).

Let us next assume $x_{l,0} < x_{l,1}$. In this case, we have $\frac{\delta(x_{l,0})+\lambda}{\delta(x_{l,1})+\lambda}\frac{\delta(x_{l,1})}{\delta(x_{l,0})} > 1$. However, the sign of $\left(1 - \frac{\beta_1(x_{l,1})}{\beta_1(x_{l,0})}\right)$ is ambiguous. Thus we have $\Pi_u \lesseqgtr \Pi^*(x_{l,0})$. This proves point b).

Finally, as can be seen, (28) is unaffected by the regulatory regime applied. Thus Π_u is the trigger point irrespective of the regime implemented. This proves point c). Proposition 2 is thus proven.■

5.0.2 Proof of Proposition 3

Define $V_{PS,i}(\Pi)$ as the value function under the old ($i = 0$) and the new ($i = 1$) regime, respectively. We first compute the closed-form solutions of the value function and of the option function after the change. Then we turn to the pre-change case. Finally, a comparison between the two trigger points obtained is made. As will be shown, they are equal.

Start with the new regime. The solution obtained is equal to that computed in the absence of policy risk. Using dynamic programming, the firm's value $V_{PS,1}(\Pi)$ can be written as

$$V_{PS,1}(\Pi) = \Pi dt + e^{-rdt}E\left[V_{PS,1}(\Pi + d\Pi)\right].$$

Expanding the right-hand side and using Itô's lemma one obtains

$$rV_{PS,1}(\Pi) = \Pi + (r - \delta(x))\Pi\frac{\partial V_{PS,1}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 V_{PS,1}(\Pi)}{\partial \Pi^2}, \qquad (29)$$

where $x = x_l, x_{h,1}$. Eq. (29) can be solved as

$$V_{PS,1}(\Pi) = \begin{cases} \frac{\Pi}{\delta(x_l)} + V_1\Pi^{\beta_1(x_l)} & \text{if} \quad \Pi < \widetilde{\Pi}_1, \\ \\ \frac{\Pi}{\delta(x_{h,1})} + V_2\Pi^{\beta_2(x_{h,1})} & \text{if} \quad \Pi > \widetilde{\Pi}_1. \end{cases} \qquad (30)$$

Similarly, the Bellman equation of the option function is obtained

$$O_{PS,1}(\Pi) = e^{-rdt}E\left[O_{PS,1}(\Pi + d\Pi)\right]$$

Expanding the right-hand side and using Itô's lemma one obtains

$$rO_{PS,1}(\Pi) = (r - \delta(x))\Pi\frac{\partial O_{PS,1}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 O_{PS,1}(\Pi)}{\partial \Pi^2}, \qquad (31)$$

where $x = x_l, x_{h,1}$. The equation (31) has the following solution

$$O_{PS,1}(\Pi, x) = \begin{cases} C_1 \Pi^{\beta_1(x_l)} & \text{if} \quad \Pi < \widetilde{\Pi}_1, \\ \\ B_1 \Pi^{\beta_1(x_{h,1})} + B_2 \Pi^{\beta_2(x_{h,1})} & \text{if} \quad \Pi > \widetilde{\Pi}_1. \end{cases} \tag{32}$$

Let us focus on the $\Pi \in \left(0, \widetilde{\Pi}_1\right)$ region. Using the VMC and SPC, we obtain the trigger point[26]

$$\Pi^* \equiv \frac{\beta_1(x_l)}{\beta_1(x_l) - 1} \delta(x_l) I = \Pi^*_{PC}(x_l), \tag{33}$$

and

$$V_1 - C_1 = -\frac{I}{\beta_1(x_l) - 1} \left[\Pi^*\right]^{-\beta_1(x_l)}. \tag{34}$$

It is easy to ascertain that $\frac{\partial(V_1 - C_1)}{\partial \Pi} = 0$.

Let us now turn to the pre-change case. To find the trigger point above which investment is profitable, we focus on the $\Pi \in \left(0, \min(\widetilde{\Pi}_0, \widetilde{\Pi}_1)\right)$ region. This entails that both the switch levels $\widetilde{\Pi}_0$ and $\widetilde{\Pi}_1$ are sufficiently high to ensure that a tighter regulation is applied only under good states. If, otherwise, at least one of the two switch points were low the profit-sharing regulation would be implemented in the bad-news region. This would lead to a distortion.

Let us start with the firm's value. The Bellman equation is

$$V_{PS,0}(\Pi) = \Pi dt + (1 - \lambda dt) e^{-rdt} E\left[V_{PS,0}(\Pi + d\Pi)\right] + \lambda dt e^{-rdt} E\left[V_{PS,1}(\Pi + d\Pi)\right].$$

Expanding the right-hand side and using Itô's lemma one obtains

$$(r + \lambda) V_{PS,0}(\Pi) = \Pi + (r - \delta(x_l)) \Pi \frac{\partial V_{PS,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2} \Pi^2 \frac{\partial^2 V_{PS,0}(\Pi)}{\partial \Pi^2} + \lambda V_{PS,1}(\Pi). \tag{35}$$

Define $X(\Pi) \equiv V_{PS,0}(\Pi) - V_{PS,1}(\Pi)$. Subtracting (29) by (35) yields

$$(r + \lambda) X(\Pi) = (r - \delta(x_l)) \Pi \frac{\partial X(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2} \Pi^2 \frac{\partial^2 X(\Pi)}{\partial \Pi^2}.$$

[26] See Proposition 1.

The function $X(\Pi)$ has a standard solution

$$X(\Pi) = \sum_{i=1}^{2} X_i \Pi^{\beta_i(x_l,\lambda)}.$$

$\beta_i(x_l, \lambda)$ are the roots of the characteristic equation

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

Given the condition $X(0) = 0$, X_2 is nil. Using the solution of $X(\Pi)$ and equation (30) we obtain

$$V_{PS,0}(\Pi) = \frac{\Pi}{\delta(x_l)} + V_1\Pi^{\beta_1(x_l)} + X_1\Pi^{\beta_1(x_l,\lambda)}, \tag{36}$$

where the parameter X_1 is an unknown to be determined.

Let us next turn to the option function. The Bellman equation is

$$O_{PS,0}(\Pi) = (1-\lambda dt)e^{-rdt}E\left[O_{PS,0}(\Pi + d\Pi)\right] + \lambda dt e^{-rdt}E\left[O_{PS,1}(\Pi + d\Pi)\right].$$

Expanding its right-hand side and using Itô's lemma yields

$$(r+\lambda)O_{PS,0}(\Pi) = (r-\delta(x_l))\Pi\frac{\partial O_{PS,0}(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 O_{PS,0}(\Pi)}{\partial \Pi^2} + \lambda O_{PS,1}(\Pi) \tag{37}$$

Define $Y(\Pi) \equiv O_{PS,0}(\Pi) - O_{PS,1}(\Pi)$. Subtracting (31) from (37) yields

$$(r+\lambda)Y(\Pi) = (r-\delta(x_l))\Pi\frac{\partial Y(\Pi)}{\partial \Pi} + \frac{\sigma^2}{2}\Pi^2\frac{\partial^2 Y(\Pi)}{\partial \Pi^2}.$$

Given the condition $Y(0) = 0$, Y_2 is nil. Using the solution of $Y(\Pi)$ and equation (37) we obtain the option function under regulatory risk

$$O_{PS,0}(\Pi) = C_1\Pi^{\beta_1(x_l)} + Y_1\Pi^{\beta_1(x_l,\lambda)}, \tag{38}$$

where the parameter Y_1 is an unknown to be determined.

Let us now compute the trigger point above which investment is profitable under policy risk. Substituting (36) and (38) into the (VMC) and (SPC) we obtain a two-equation system

$$\frac{\Pi}{\delta(x_l)} + (V_1 - C_1)\,\Pi^{\beta_1(x_l)} + (X_1 - Y_1)\,\Pi^{\beta_1(x_l,\lambda)} - I = 0, \tag{39}$$

$$\frac{1}{\delta(x_l)} + \beta_1(x_l)\,(V_1 - C_1)\,\Pi^{\beta_1(x_l)-1} + \beta_1(x_l,\lambda)\,(X_1 - Y_1)\,\Pi^{\beta_1(x_l,\lambda)} = 0. \quad (40)$$

Divide (40) by $\beta_1(x_l, \lambda)$ and substitute it into (39) so as to obtain

$$\left[\frac{\beta_1(x_l,\lambda)-1}{\beta_1(x_l,\lambda)}\right]\frac{\Pi}{\delta(x)} + \left[\frac{\beta_1(x_l,\lambda)-\beta_1(x_l)}{\beta_1(x_l,\lambda)}\right](V_1 - C_1)\,\Pi^{\beta_1(x_l)} - I = 0. \quad (41)$$

Substitute (34) into (41) and multiply it by $\frac{\beta_1(x_l)-1}{\beta_1(x_l)}\frac{1}{I}$. We thus obtain

$$\left[\frac{\beta_1(x_l,\lambda)-1}{\beta_1(x_l,\lambda)}\right]\left(\frac{\Pi}{\Pi^*}\right) - \left[\frac{\beta_1(x_l,\lambda)-\beta_1(x_l)}{\beta_1(x_l,\lambda)}\right]\left(\frac{\Pi}{\Pi^*}\right)^{\beta_1(x_l)} - \frac{\beta_1(x_l)-1}{\beta_1(x_l)} = 0. \quad (42)$$

Multiply (42) by $\frac{\beta_1(x_l,\lambda)}{\beta_1(x_l,\lambda)-1}$ so as to obtain

$$\left(\frac{\Pi}{\Pi^*}\right) - \frac{\beta_1(x_l,\lambda)-\beta_1(x_l)}{[\beta_1(x_l,\lambda)-1]\,\beta_1(x_l)}\left(\frac{\Pi}{\Pi^*}\right)^{\beta_1(x_l)} - \frac{\beta_1(x_l,\lambda)\,[\beta_1(x_l)-1]}{[\beta_1(x_l,\lambda)-1]\,\beta_1(x_l)} = 0.$$

Adding and subtracting 1 from the LHS yields

$$\left[\left(\frac{\Pi}{\Pi^*}\right) - 1\right] - \frac{\beta_1(x_l,\lambda)-\beta_1(x_l)}{[\beta_1(x_l,\lambda)-1]\,\beta_1(x_l)} \cdot \left[\left(\frac{\Pi}{\Pi^*}\right)^{\beta_1(x_l)} - 1\right] = 0. \quad (43)$$

Define $y \equiv \left(\frac{\Pi}{\Pi^*}\right)$and $\phi \equiv \frac{\beta_1(x_l,\lambda)-\beta_1(x_l)}{[\beta_1(x_l,\lambda)-1]\beta_1(x_l)} < 1$. Thus, eq. (43) can be rewritten as

$$y - 1 = \phi\left(y^{\beta_1(x_l)} - 1\right). \quad (44)$$

Equation (44) has more than one solution. We thus compute these solutions and identify the optimal one. As can be noted, solution $y = 1$ holds in equation (44). This entails that $\Pi^{**} = \Pi^*$. Substituting Π^* into system (39)-(40) one thus obtains $(X_1 - Y_1) = 0$. This is the first couple of solutions of system (39)-(40).

Define $y\prime$ as any other solution. Given inequalities $\beta_1(x_l) > 1$, $\phi < 1$ and $\beta_1(x_l)\phi < 1$, it is easy to show that any other solution is $y\prime > 1$. This implies that the trigger point obtained would be $\Pi^{**} > \Pi^*$. Substituting this new solution into system (39)-(40) yields $(X_1 - Y_1) > 0$. Thus $(\Pi^{**} > \Pi^*, (X_1 - Y_1) > 0)$ is the second couple of solutions. However this couple is sub-optimal. To show this, assume *ab absurdo* that $(\Pi^{**} > \Pi^*, (X_1 - Y_1) > 0)$ is the optimal solution. Then, using the definitions of $X(\Pi)$ and $Y(\Pi)$, we define the pre-reform project's payoff, net of both the opportunity and the effective cost, as

$$F(\Pi) \equiv [V_{PS,0}(\Pi) - O_{PS,0}(\Pi) - I] \tag{45}$$

Using (VMC) and eq. (45) we obtain $F(\Pi^{**}) = 0$. Rewrite (45) as

$$F(\Pi) = [V_{PS,1}(\Pi) - O_{PS,1}(\Pi) - I] + (X_1 - Y_1)\,\Pi^{\beta_1(x_l,\lambda)}.$$

Since in $\Pi = \Pi^*$ the post-reform project's payoff $[V_{PS,1}(\Pi) - O_{PS,1}(\Pi) - I]$ is nil, we know that $F(\Pi^*) = (X_1 - Y_1)\,\Pi^{*\beta_1(x_l,\lambda)} > 0$. Namely, in the interval $\Pi \in (0, \Pi^{**})$, there exists at least one point ($\Pi = \Pi^*$) such that the project's payoff is strictly positive. Thus, a rational firm facing a positive payoff in $\Pi = \Pi^*$, immediately invests instead of waiting until the trigger point Π^{**} is reached. This contradicts the assessment that ($\Pi^{**} > \Pi^*, (X_1 - Y_1) > 0$) is the optimal solution. Therefore, the remaining solution ($\Pi^{**} = \Pi^*, (X_1 - Y_1) = 0$) is the optimal one. This proves Proposition 3.■

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