Optimal regulation of lumpy investments*

Peter Broer† and Gijsbert Zwart‡

June 29, 2012

Abstract

We study optimal timing of regulated investment in a real options setting, in which the regulated monopolist has private information on investment costs. In solving the ensuing agency problem, the regulator trades off investment timing inefficiency against the deadweight loss arising from high price caps. We show that optimal regulation is implemented by a price cap that decreases as a function of the monopolist's chosen investment time.

Keywords: real options, asymmetric information, agency, optimal regulation, budget constraint

JEL classification: D81, D82, L51.

1. Introduction

Current regulation of network industries emphasizes price cap schemes and the efficiency gains they bring. But whether such schemes will also succeed in securing the large new investments that network sectors face has been called into question (see Vogelsang, 2010, for a discussion). In energy transmission, large new investments will be needed to allow new renewable energy

*We thank the TREIN working group, participants in the Mannheim CLEEN 2012 workshop, as well as Jan Boone, Victoria Shestalova and Bert Willems for useful comments. We gratefully acknowledge the financial support of Agentschap NL.

†Netherlands Bureau for Economic Policy Analysis, CPB, PO Box 80510, 2508 GM The Hague, The Netherlands, e-mail: p.broer@cpb.nl

‡TILEC, Tilburg University, and Netherlands Bureau for Economic Policy Analysis, CPB, PO Box 80510, 2508 GM The Hague, The Netherlands, e-mail: g.t.j.zwart@cpb.nl.

sources to be connected to the grid[1]. Likewise, telecom networks face costly upgrades in their transition into Next-generation networks, to support new demands on capacity for high speed Internet applications (see e.g. Cambini and Jiang, 2009). Timely investment by regulated firms will depend on the regulatory schemes these firms are exposed to.

In this paper, we explore how regulation can incentivize efficient timing of large, one-off, irreversible investments ("lumpy investments") under uncertain demand growth. It is well-known that under demand uncertainty, investments are optimally delayed beyond the point where investment costs equal benefits: by investing, one also gives up a valuable real option to delay investment (McDonald and Siegel, 1986) and this constitutes an additional opportunity cost. An unregulated monopolist's private incentives to invest are typically weaker than social ones, as the firm cannot appropriate all benefits, but does incur all costs. As a result, the monopolist tends to delay investment even longer.

Price regulation is an effective instrument for reducing dead-weight loss after investments have taken place. Ex ante, however, price regulation also impacts on the monopolist's investment timing. Simple price caps can in general not fully restore both optimal investment and optimal post-investment pricing, as was shown in Dobbs (2004) and subsequent papers on regulation under uncertainty (see Guthrie, 2006; Cambini and Jiang, 2009, for reviews). In case of a single regulated investment, ex-post price caps only reduce surplus available to the monopolist and further undermine its incentives to invest early. The goals of reducing dead-weight loss and speeding up investment are then conflicting and cannot both be achieved with a single instrument.

If the regulator also observes realised demand, it may condition its regulatory scheme on this information as well. We analyse optimal regulation in a model involving a single large investment, when the regulator can contract with the monopolist both on ex-post pricing and on the level of demand at the moment investment takes place. When there is no asymmetry of information, the solution is simply to tell the monopolist when to invest, and to set prices optimally. The optimal timing and pricing decisions are related in the relevant case when investment costs have to be recovered through ex post revenues, and we solve for the second-best combination of timing and price.

[1]For example, UK regulator Ofgem issued the Transmission Operator Incentives programme to provide a funding framework for some 5 billion pounds of new transmission investments. These are necessary accommodate the generation connections that are part of the UK government's 2020 targets for ensuring a transition to a low-carbon electricity sector.

Our main interest is in the situation where the monopolist has an informational advantage over the regulator. Following the seminal Baron and Myerson (1982) model, we consider the case where investment costs c are private information to the monopolist; the regulator only knows the distribution of these costs, with density $f(c)$. Optimal regulation in this case has to respect an incentive compatibility constraint in addition to the budget constraint. This requires leaving positive information rents to all monopolist types except for the least efficient one. These rents are socially costly, since they need to be paid for by allowing higher price caps, which in turn introduce higher dead-weight losses. In order to reduce these informational rents, the regulator will optimally delay investment timing for higher-cost firms beyond the second-best timing. This will reduce the present value of mimicking a less efficient firm, and relax the incentive compatibility constraint, resulting in lower information rents and, consequently, lower pricing distortions. Finally, we show that the optimal regulation can be implemented by offering the monopolist a price cap that is decreasing in the demand level at which investment occurs. Such a scheme incentivizes more efficient firms not to delay investment, as the gains of waiting until demand is higher are more than wiped out by the decline in allowed price level.

Our approach combines the real options literature on regulation under uncertainty with the mechanism design literature on optimal regulation. The former literature, which builds on Dobbs (2004)[2], studies how standard price caps interact with investment timing in a stochastic, real options environment. Extensions of this work are, for instance, Evans and Guthrie (2005), who look at the determination of the rate base for setting prices, Guthrie, Small and Wright (2006), focussing on stochastic costs, Moretto, Panteghini and Scarpa (2008), who look at profit sharing rules instead of price caps, and Roques and Savva (2009) studying the case of duopoly rather than monopoly. We add to this literature by making explicit the information asymmetry that drives imperfect regulation. Hence we do not have to take the type of regulation as given, but can explore what optimal regulation would be. We build on the theory of optimal regulation under a budget constraint, where the regulator cannot make transfers to the firm and the firm's costs have to be recovered through linear prices[3]. We apply this theory to the investment-under-uncertainty problem at hand.

In looking at agency conflicts within a real options setting, our work is related to contributions by Grenadier and Wang (2005), Hori and Osano (2009) and Shibata (2009) in the area of corporate finance. These papers study incentive contracts inducing firm managers to make

[2]Surveys are Guthrie (2006) and, more recently, Cambini and Jiang (2009)

[3]See Schmalensee (1989), and Laffont and Tirole (1993, Chapter2.7)

timely investment on behalf of a firm owner. In the present paper, we consider the regulator-monopolist agency relation. One important difference with these corporate finance applications is that in our context, the cost of leaving rents to the monopolist (the agent) is the distortion resulting from prices above marginal cost. Technically, trading off these dead-weight loss distortions against inefficient timing requires solving an additional optimal control problem. In addition, we show how the optimal contract can be straightforwardly implemented in the form of an investment timing dependent price cap.

The paper proceeds as follows. We first outline first-best investment under uncertainty, and then study how optimal timing changes if variable prices have to be raised above marginal costs to allow the firm to break even (the second-best benchmark). We demonstrate that a regulator cannot implement the second-best using only a price cap, in which case he has to trade off inefficient timing against ex-post dead-weight loss. In section 3 we study optimal regulation under asymmetric information, and demonstrate that this involves setting a price cap that declines as the firm waits longer. Section 4 concludes.

2. The model

A regulated monopolist can make an irreversible single investment in a project that, once constructed, allows the monopolist to keep on selling the project's output from that time onwards. For simplicity, we consider the limit of very large capacity, so that we can ignore binding capacity constraints after the project has been constructed. The flow of net consumer benefits at time t equal $A_t v(p)$, with time-dependent A_t a stochastic demand shift parameter, and stationary function $v(p)$ the normalized net consumer surplus at price p. The derivative of v equals minus normalized demand, $dv/dp = -q(p)$.[4] We focus on constant elasticity demand, with (stationary) elasticity $0 < \eta < 1$, so that

$$q(p) = p^{-\eta}.$$

[4]This follows from the envelope theorem: if gross consumer surplus from consuming q units equals $u(q)$, then $v(p) = \max_q u(q) - pq$, and hence $\frac{dv}{dp} = -q$.

To ensure that the flow of total consumer surplus at price p is finite at all times, we truncate demand at a maximum willingness-to-pay $\bar{p}$. Total consumer surplus $v(p)$ then takes the form

$$v(p) = \frac{\bar{p}^{1-\eta} - p^{1-\eta}}{1-\eta}. \tag{1}$$

We assume $\bar{p}$ to be sufficiently high that it will always be greater than the optimal price caps explored in the following.

The demand shift parameter A_t follows geometrical Brownian motion with drift μ and volatility σ,

$$dA_t = \mu A_t dt + \sigma A_t dz, \tag{2}$$

and A_t is observable to both the monopolist and its regulator. The total present value of consumer surplus of a completed project, when price is fixed at p, and when current demand is at A_0, equals

$$V(A_0, p) = E\left(\int_0^\infty e^{-rt} A_t v(p) dt \middle| A(t=0) = A_0\right) = \frac{A_0 v(p)}{r-\mu}, \tag{3}$$

where $r > \mu$ is the discount rate.

The costs of investment equal c, which is the realization of a random variable with density $f(c)$ on support $[c_L, c_H]$. We assume f has monotone hazard rate, i.e. $F/f(c)$ is non-decreasing. While the monopolist itself observes the value of c, in the asymmetric information setting the regulator only knows the density $f(c)$. Marginal costs of selling the project's output (e.g. capacity on the network) are assumed to be zero[5]. If investment occurs at demand level A, the net present value of the monopolist's surplus at the moment of investment equals, given a constant price p,

$$\pi(A, p) = \frac{Apq(p)}{r-\mu} - c = \frac{Ap^{1-\eta}}{r-\mu} - c.$$

In the following, we shall be interested in optimal investment timing and pricing decisions.

[5]Inclusion of marginal costs is relatively straightforward, but complicates the sufficient conditions for the monotonicity that the optimal mechanism should satisfy.

3. Optimal investment timing

Before analysing the optimal regulation of investment in the presence of asymmetric information on investment costs c, let us first consider two benchmark solutions in which c is common knowledge: first-best investment, where the regulator can remunerate the monopolist using a socially costless transfer, and the second-best where investment costs have to be recovered through a non-zero variable price p.

Welfare-optimal timing of the investment depends on the realization of costs, and on the level of the price p. In the first-best, the variable price p should be zero: marginal costs are zero and increasing p would introduce underconsumption and an ensuing dead-weight loss. In this first-best situation, the monopolist recovers his investment costs c through a socially costless transfer payment. Using standard real options arguments (see e.g. Dixit and Pindyck, 1994), first-best investment occurs at the (stochastic) moment $T(\bar{A})$ when demand parameter A for the first time reaches some threshold value $\bar{A}$. When the current ($t = 0$) demand parameter A equals $A_0 < \bar{A}$, current total welfare equals the expected discounted welfare from investing when A first reaches $\bar{A}$:

$$\begin{aligned} W(A_0, \bar{A}) &= E\left(e^{-rT(\bar{A})}\left(\frac{\bar{A}v(0)}{r-\mu} - c\right)\Big|A(t=0) = A_0\right) \\ &= \left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}\bar{p}^{1-\eta}}{(1-\eta)(r-\mu)} - c\right). \end{aligned} \tag{4}$$

In the second line, we used that (see e.g. Dixit and Pindyck, 1994, section 9.A)

$$E\left(e^{-rT(\bar{A})}\big|A(t=0) = A_0\right) = \left(\frac{A_0}{\bar{A}}\right)^{\lambda},$$

where $\lambda > 1$ is the positive root of the characteristic equation associated with the stochastic process.[6] Maximization of total welfare (4) over the threshold $\bar{A}$ then immediately gives the first-best investment threshold $\bar{A}^{fb}$:

Lemma 1 *First-best investment involves setting variable price $p = 0$, and investing as soon as the demand shift A reaches a cost-dependent threshold $\bar{A}^{fb}(c)$ given by*

$$\bar{A}^{fb}(c)\frac{\bar{p}^{1-\eta}}{(1-\eta)(r-\mu)} = \frac{\lambda}{\lambda-1}c. \tag{5}$$

[6] i.e., λ satisfies $\frac{1}{2}\sigma^2\lambda(\lambda-1) + \mu\lambda = r$.

In particular, investment is optimally delayed beyond the moment when benefits equal costs c. This is a result of the well-known option value of waiting to invest for discrete irreversible investments (McDonald and Siegel, 1986). Since investment is irreversible, waiting has an option value as it protects the investor in case demand should decline. In the low volatility limit where uncertainty vanishes, $\lambda \to \infty$ and we find that optimal investment occurs when benefits equal costs.

Consider next the second-best, where transfer payments from the regulator to the monopolist are not available, and investment costs have to be recovered through a positive variable price, $p > 0$. The positive price creates a dead-weight loss that depends on the elasticity of demand. To minimize dead-weight loss it will be optimal to set the price such that the firm only just breaks even,

$$\begin{aligned} \Pi &= E\left(e^{-rT(\bar{A})}\left(\frac{\bar{A}pq(p)}{r-\mu} - c\right)\Big| A(t=0) = A_0\right) \\ &= \left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}pq(p)}{r-\mu} - c\right) = 0. \end{aligned} \tag{6}$$

The positive price, required to satisfy the break-even constraint creates a welfare loss and hence decreases available surplus upon investment. Optimal investment timing will be delayed compared to the first-best, not only because surplus is lower, but also because the required price distortion decreases as the investment threshold $\bar{A}$ increases, as the revenues then can be raised over a larger demand.

To solve for optimal investment timing, we maximize total surplus subject to the break-even constraint (6),

$$\max_{\bar{A},p}\left[\left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}\left(\bar{p}^{1-\eta} - p^{1-\eta}\right)}{(1-\eta)(r-\mu)}\right)\right] \tag{7}$$

$$\text{s.t.} \quad \left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}p^{1-\eta}}{r-\mu} - c\right) = 0.$$

Solving this constrained optimization programme gives us second-best investment threshold $\bar{A}^{sb}(c)$, and the optimal price $p^{sb}(c)$:

Lemma 2 *Second-best investment involves investing as soon as the demand shift A reaches a* *threshold $\bar{A}^{sb}(c)$ that is given by*

$$\frac{\bar{A}^{sb}(c)\bar{p}^{1-\eta}}{r-\mu} = \frac{\lambda}{\lambda-1}c. \tag{8}$$

The required second-best price satisfies

$$\left(\frac{p^{sb}}{\bar{p}}\right)^{1-\eta} = \frac{\lambda-1}{\lambda}. \tag{9}$$

The proof of this lemma and the following propositions can be found in the appendix.

Note that if demand is completely inelastic, $\eta = 0$, second-best timing equals first-best timing (5). There is no dead-weight loss in this case, and choosing positive p to satisfy the profit constraint does not interfere with optimal timing.

When the regulator is perfectly informed about costs c, second-best investment can obviously be implemented by mandating investment at the second-best demand level $\bar{A}^{sb}(c)$, and capping price at $p^{sb}(c)$. More important to note is that second-best investment cannot be implemented by only setting a price cap level p_c and leave the firm to choose its privately optimal investment threshold, except in the case when demand is completely inelastic ($\eta = 0$):

Proposition 1 *If the regulator can only set a price cap p_c, and cannot influence investment timing $\bar{A}$ directly, second-best timing can only be achieved by setting the price cap at the maximum willingness to pay, $p_c = \bar{p}$. Setting $p_c = p^{sb}$ leads to inefficient delay of investment. The optimal price cap satisfies*

$$\left(\frac{p_c}{\bar{p}}\right)^{1-\eta} = \frac{\lambda-1}{\lambda-(1-\eta)}, \tag{10}$$

so that $p^{sb} \leq p_c \leq \bar{p}$.

If the price cap is set at maximum willingness to pay $\bar{p}$, the monopolist captures all available surplus, and as a result implements optimal timing. This comes at significant social cost, however, as the high price reduces demand below its optimal level. For lower price caps, on the other hand, the monopolist does not internalize consumer surplus in making its investment decision, and as a result waits inefficiently long (as in Dobbs, 2004). In the optimum, the negative effects of delay are traded off against the inefficiency of excessive dead-weight loss.

4. Asymmetric information

We now turn to the case of main interest, where c is not observed by the regulator: the regulator only knows the distribution of costs, with density $f(c)$, $c \in [c_L, c_H]$. In designing its regulation, the regulator therefore faces an agency problem. In our search for the optimal regulatory policy in this asymmetric information environment, by the revelation principle[7] we can focus on direct incentive compatible mechanisms: the regulator offers the monopolist a choice from a menu of contracts $(\bar{A}(\hat{c}), p(\hat{c}))$ that depend on a cost level $\hat{c}$ that is to be announced by the monopolist. Confronted with this menu, the monopolist will choose to announce cost level $\hat{c}$ that maximizes his expected present value of profits:

$$\Pi(\bar{A}, p, c) = \max_{\hat{c}} \left(\frac{A_0}{\bar{A}(\hat{c})} \right)^{\lambda} \left(\frac{\bar{A}(\hat{c}) p(\hat{c})^{1-\eta}}{r - \mu} - c \right).$$

Incentive compatibility of the mechanism (i.e., the monopolist will maximise its profits by choosing $\hat{c} = c$) is then equivalent to the conditions (see e.g. Fudenberg and Tirole, 1991, Ch.7)

$$\frac{\mathrm{d}\Pi}{\mathrm{d}c} = - \left(\frac{A_0}{\bar{A}(c)} \right)^{\lambda}, \tag{11}$$

$$\frac{\mathrm{d}\bar{A}(c)}{\mathrm{d}c} \geq 0 \tag{12}$$

The regulator has to leave information rents to the monopolist to induce it to reveal its costs, and by equation (11) these rents increase as c gets lower. We assume that the regulator needs to give non-negative rents to all cost-types (the monopolist's participation constraint), and in view of (11) it then suffices to make sure that the highest type makes zero profits, $\Pi(c_H) = 0$.

The regulator's objective is to optimize expected welfare, subject to these incentive and participation constraints, and to do so it has to solve the following optimal control problem[8]

$$\max_{\bar{A}(c), p(c)} \int_{c_L}^{c_H} \left[\left(\frac{A_0}{\bar{A}} \right)^{\lambda} \left(\frac{\bar{A}(\bar{p}^{1-\eta} - p^{1-\eta})}{(1-\eta)(r-\mu)} \right) + \Pi(c) \right] \mathrm{d}F(c) \tag{13}$$

[7] See e.g. Fudenberg and Tirole (1991, Ch.7).

[8] As will become clear, the monotonicity constraint (12) on $\bar{A}$ will hold by virtue of the monotone hazard rate assumption on f

s.t.

$$\Pi(c) = \left(\frac{A_0}{\bar{A}}\right)^{\lambda} \left(\frac{\bar{A}p^{1-\eta}}{r-\mu} - c\right) \tag{14}$$

$$\frac{\mathrm{d}\Pi(c)}{\mathrm{d}c} = -\left(\frac{A_0}{\bar{A}}\right)^{\lambda} \tag{15}$$

$$\Pi(c_H) = 0 \tag{16}$$

The standard (Baron and Myerson, 1982) trade-off embodied in the problem is that on the one hand, the regulator would like to reduce information rents $\Pi(c)$, as these require distortionary prices. But reducing the information rents can only be achieved by inefficient delay (high $\bar{A}$) for some types, in view of the incentive constraint (11). The trade-off gets more severe as elasticity η gets larger and the dead-weight loss induced by high information rents increases.

The solution to problem (13) is as follows (proofs are in the appendix).

Proposition 2 *The optimal menu offered by the regulator is given by combinations of investment thresholds and associated price caps $(\bar{A}(c), p(c))$ satisfying*

$$\frac{\bar{A}(c)\bar{p}^{1-\eta}}{r-\mu} = \frac{\lambda}{\lambda-1}\left(c + \eta\frac{F}{f}(c)\right), \tag{17}$$

$$\bar{A}(c)p(c)^{1-\eta} = c + \left(c + \eta\frac{F}{f}(c)\right)^{\lambda} \int_{c}^{c_H} \left(c' + \eta\frac{F}{f}(c')\right)^{-\lambda} dc'. \tag{18}$$

for cost parameters $c \in [c_L, c_H]$.

From the solution to programme (13), equations (17), (18), we see that when $\eta = 0$, we again have optimal investment timing as in lemma 1. It is then socially costless to pay the required information rents $\Pi(c)$. With $\eta > 0$, optimal investment is delayed: since we assume linear pricing, even the most efficient type's investment timing is distorted away from the first-best. However, the lowest type's investment threshold $\bar{A}(c_L)$ does equal the *second-best* result $\bar{A}^{sb}(c_L)$ from lemma 2, even though under asymmetric information the firm gets a positive rent $\Pi(c_L)$, which has to be paid for through an elevated price $p(c_L) > p^{sb}$. This second-best timing result is special to the constant elasticity case under consideration, in which two opposing effects on timing precisely cancel. On the one hand, positive required profits $\Pi(c_L)$ will increase dead-weight loss and reduce total available welfare upon investing. This lower available surplus upon investing would tend to make delaying the investment time optimal. But on the other hand, by speeding up investment, profits arrive earlier and the required price rise to make sure current discounted expected profits equal $\Pi(c_L)$ is lower. This effect tends to make faster investment optimal. For the case of constant elasticity demand, the two effects precisely cancel. This is consistent with the observation in the proof of lemma 2 that the second-best threshold is indeed independent of required producer rents Π.

For all higher costs $c > c_L$, optimal investment thresholds under asymmetric information are later than second-best levels. Delayed investment reduces profits (by the incentive constraint) for more efficient types, which reduces dead-weight loss for those types.

While the optimal direct mechanism gives a parametrised menu of contracts $(\bar{A}(c), p(c))$, the mechanism can be straightforwardly implemented by offering the firm a price-cap that is a function of the investment timing, $p(\bar{A})$, since $\bar{A}(c)$ is strictly increasing in c:

Corollary 1 *The regulator can implement the optimal mechanism (17,18) by offering the monopolist a price cap that depends on its chosen investment threshold, $p(\bar{A})$. The function $p(\bar{A})$ is decreasing.*

Intuitively, low-cost types are induced to invest early because the price declines by more than made up for by the increased demand from waiting. Higher cost types, on the other hand, benefit more from delaying their higher capital outlays, and choose the higher threshold in spite of the lower associated price cap.

As an example, in figure 1 we sketch the required functional form of $p(\bar{A})$ when costs are uniformly distributed. In that case, $F/f(c) = c - c_L$, and we can explicitly work out expressions (17),(18) to get

$$\frac{\bar{A}(c)\bar{p}^{1-\eta}}{r-\mu} = \frac{\lambda}{\lambda-1}\left(c + \eta(c - c_L)\right),$$
$$\left(\frac{p(c)}{\bar{p}}\right)^{1-\eta} = \frac{1}{\lambda(1+\eta)}\left(\frac{(1+\eta)\lambda c - \eta c_L}{(1+\eta)c - \eta c_L} - \left(\frac{(1+\eta)c - \eta c_L}{(1+\eta)c_H - \eta c_L}\right)^{\lambda-1}\right).$$

As is clear from figure 1, firms are discouraged from socially inefficient delay by a price cap that declines with the demand level at which they invest. The longer a firm waits, the lower the per-unit price. High-cost firms, conversely, do not find it profitable to speed up investment, as demand size would then be insufficient to benefit from the higher price.

The graph further shows that as elasticity increases, the dead-weight cost of increased prices grows, and the optimal schedule tends to have lower price caps and longer investment delays.

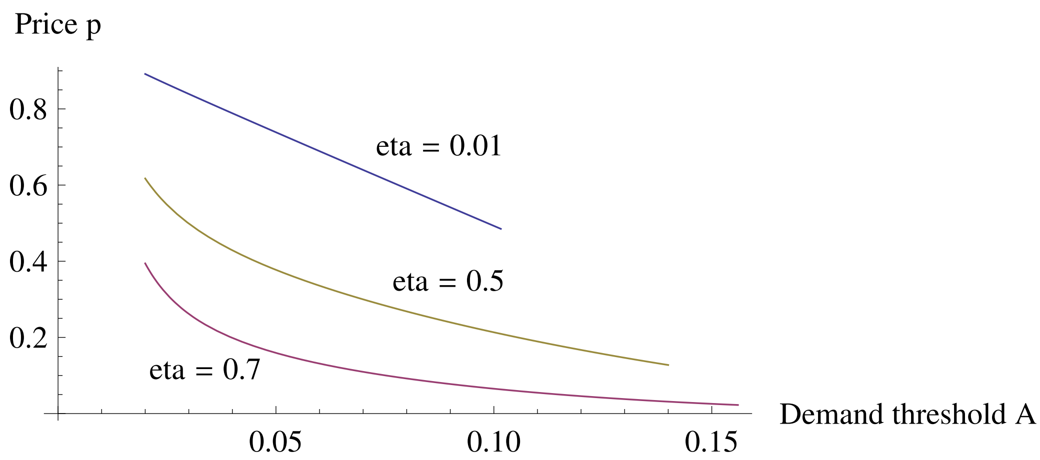

Figure 1: Optimal price-cap schedule as a function of investment moment $\bar{A}$, for uniform cost-distribution and for three values of elasticity η. Other parameter values are $\bar{p} = 1 = r - \mu, \lambda = 2, c_L = 0.01, c_H = 0.05$.

5. Conclusion

We derived optimal regulation of infrastructure investments under uncertainty when demand is observable. Under pure price caps, a monopolist inefficiently delays investment. We show that this delay can be mitigated by offering the monopolist a price cap that decreases with demand. Under constant elasticity demand, we show that the most efficient type invests at the second-best moment. As is usual, less efficient types' investments are delayed to reduce the prices (and associated dead-weight loss) necessary to pay for the more efficient types' rents.

In practice, data on demand is often likely to be available after investment. Regulators often use a mix of rate of return and price cap mechanisms, monitoring not only prices but also total revenues. Demand over the first period after investment can then be a proxy for demand at the moment of investment itself.

This paper considers a greenfield investment: the monopolist is not active before the investment. One natural extension of our approach would be to allow for existing regulated activities, and to explore how regulation of those activities could be used to incentivize investment in the new infrastructure. It is well known (Guthrie, 2006) that regulation before investment affects opportunity costs of investing in capacity expansion. One way of exploring this is by considering a situation of continuous investment, as in Dobbs (2004), and to analyse optimal regulation in that context.

A crucial assumption in our approach is that the regulator has strong commitment power.

The investment problem is inherently dynamic, and the optimal regulation induces firms to reveal their types (costs) gradually over time, as they choose their investment timing. But this introduces opportunities for renegotiation (see Laffont and Tirole, 1993, chapter 10), as after more efficient types have been screened, the rationale for inefficient delays vanishes. An analysis with the additional constraint that the contracts are renegotiation proof at any point in time is likely to be challenging.

References

Baron, David P. and Roger B. Myerson. 1982. "Regulating a Monopolist with Unknown Costs." *Econometrica* 50(4):911–930.

Cambini, C. and Y. Jiang. 2009. "Broadband investment and regulation: A literature review." *Telecommunications Policy* 33:559–574.

Dixit, A. and R. Pindyck. 1994. *Investment under uncertainty.* Princeton University Press.

Dobbs, Ian M. 2004. "Intertemporal Price Cap Regulation under Uncertainty." *The Economic Journal* 114:421–440.

Evans, L. T. and G. A. Guthrie. 2005. "Risk, Price Regulation, and Irreversible Investment." *International Journal of Industrial Organization* 23:109–128.

Fudenberg, D. and J. Tirole. 1991. *Game theory.* MIT Press.

Grenadier, S.R. and N. Wang. 2005. "Investment timing, agency, and information." *Journal of Financial Economics* 75:493–533.

Guthrie, G. 2006. "Regulating Infrastructure: The Impact on Risk and Investment." *Journal of Economic Literature* 44:925–972.

Guthrie, G., J. Small and J. Wright. 2006. "Pricing Access: Forward-looking Versus Backward-looking Cost Rules." *European Economic Review* 50:1767–1789.

Hori, K. and H. Osano. 2009. "Optimal timing of management turnover under agency problems." *Journal of Economic Dynamics and Control* 33:1962–1980.

Laffont, J.-J. and J. Tirole. 1993. *A theory of procurement and regulation.* MIT Press, Cambridge.

McDonald, R. and D. Siegel. 1986. "The Value of Waiting to Invest." *Quarterly Journal of Economics* 101.

Moretto, M., P. Panteghini and C. Scarpa. 2008. "Profit sharing and investment by regulated utilities: A welfare analysis." *Review of Financial Economics* 17(4):315–337.

Roques, F. A. and N. S. Savva. 2009. "Investment under uncertainty with price ceilings in oligopolies." *Journal of Economic Dynamics and Control* 33(2):507–524.

Schmalensee, R. 1989. "Good regulatory regimes." *Rand Journal of Economics* 20:417–436.

Shibata, T. 2009. "Investment timing, asymmetric information, and audit structure: A real options framework." *Journal of Economic Dynamics and Control* 33:903–921.

Vogelsang, I. 2010. "Incentive Regulation, Investments and Technological Change." CESifo Working paper 2964.

A. Appendix

Proof of lemma 2

For future reference, we solve the slightly more general problem where the monopolist's discounted expected profits (i.e. revenues minus investment costs) at time 0 are constrained to be at some non-negative fixed level $\Pi \geq 0$, rather than zero. We have to solve the programme

$$\max_{\bar{A},p} \left[\left(\frac{A_0}{\bar{A}}\right)^{\lambda} \left(\frac{\bar{A}\left(\bar{p}^{1-\eta} - p^{1-\eta}\right)}{(1-\eta)(r-\mu)}\right) + \Pi \right]$$

s.t.

$$\left(\frac{A_0}{\bar{A}}\right)^{\lambda} \left(\frac{\bar{A}p^{1-\eta}}{r-\mu} - c\right) = \Pi.$$

With ν the Lagrange multiplier on the constraint, the first-order condition for p yields

$$\nu = \frac{1}{1-\eta}. \tag{19}$$

For the first-order condition for the threshold demand level $\bar{A}$ we find

$$(\lambda - 1)\frac{\bar{A}\left(\bar{p}^{1-\eta} - p^{1-\eta}\right)}{(1-\eta)(r-\mu)} + \nu(\lambda - 1)\left(\frac{\bar{A}p^{1-\eta}}{r-\mu}\right) = \lambda\nu c. \tag{20}$$

Substituting ν we obtain the desired second-best threshold $\bar{A}^{sb}$ (8) from the lemma, which turns out to be independent of the value of Π. The optimal price p then follows from substituting this threshold $\bar{A}^{sb}$ in the constraint, and setting $\Pi = 0$. *Q.E.D.*

Proof of Proposition 1

Consider a price cap $p_c \leq \bar{p}$. The monopolist will choose investment threshold $\bar{A}$ to optimize his expected profits

$$\Pi(\bar{A}) = \left(\frac{A_0}{\bar{A}}\right)^{\lambda} \left(\frac{\bar{A}p_c^{1-\eta}}{r-\mu} - c\right),$$

and solving the first-order condition gives

$$\frac{\bar{A}p_c^{1-\eta}}{r-\mu} = \frac{\lambda}{\lambda - 1}c. \tag{21}$$

Comparing with second-best, (8), we find $\bar{A} \geq \bar{A}^{sb}$, with equality only when $p_c = \bar{p}$. The optimal price cap involves trading off timing inefficiency against lower ex-post pricing, maximizing social surplus:

$$\left(\frac{A_0}{\bar{A}(p_c)}\right)^{\lambda}\left(\frac{\bar{A}(p_c)(\bar{p}^{1-\eta}-p_c^{1-\eta})}{(1-\eta)(r-\mu)}+\frac{\bar{A}(p_c)p_c^{1-\eta}}{r-\mu}-c\right),$$

with $\bar{A}(p_c)$ the solution to (21). Solving the first-order condition for p_c gives

$$\left(\frac{p_c}{\bar{p}}\right)^{1-\eta}=\frac{\lambda-1}{\lambda-1+\eta}.$$

Q.E.D.

Proof of Proposition 2

For convenience we recall the programme to be solved:

$$\max_{\bar{A}(c),p(c)}\int_{c_L}^{c_H}\left[\left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}(\bar{p}^{1-\eta}-p^{1-\eta})}{(1-\eta)(r-\mu)}\right)+\Pi(c)\right]\mathrm{d}F(c) \tag{22}$$

s.t.

$$\Pi(c)=\left(\frac{A_0}{\bar{A}}\right)^{\lambda}\left(\frac{\bar{A}p^{1-\eta}}{r-\mu}-c\right) \tag{23}$$

$$\frac{\mathrm{d}\Pi(c)}{\mathrm{d}c}=-\left(\frac{A_0}{\bar{A}}\right)^{\lambda} \tag{24}$$

$$\Pi(c_H)=0 \tag{25}$$

This is an optimal control problem with constraints, with $\Pi(c)$ the state variable. To solve it, introduce co-state variable $\omega(c)$, and Lagrange multiplier $\nu(c)$ for the definition of $\Pi(c)$ in terms of the control variables $\bar{A}(c), p(c)$, as before. Optimization requires

$$\frac{\mathrm{d}\omega(c)}{\mathrm{d}c}=\nu(c)-f(c),\quad \omega(c_L)=0,\quad \Pi(c_H)=0,$$

as well as the first-order conditions for $p(c)$ and $\bar{A}(c)$. Considering first the first-order condition for $p(c)$:

$$-f(c)+(1-\eta)\nu(c)=0$$

or

$$\nu(c)=\frac{f(c)}{1-\eta}.$$

Hence

$$\omega(c) = \frac{\eta F(c)}{1-\eta}.$$

Secondly, the first-order condition for $\bar{A}(c)$ is

$$(\lambda - 1)\left(\frac{\bar{A}\left(\bar{p}^{1-\eta} - p^{1-\eta}\right)}{(1-\eta)(r-\mu)} + \frac{\nu}{f}\left(\frac{\bar{A}p^{1-\eta}}{r-\mu}\right)\right) = \lambda\frac{\omega}{f} + \lambda\frac{\nu}{f}c, \tag{26}$$

which reduces to the desired optimal threshold

$$\frac{\bar{A}(c)\bar{p}^{1-\eta}}{r-\mu} = \frac{\lambda}{\lambda-1}\left(c + \eta\frac{F}{f}(c)\right). \tag{27}$$

Note that as a result of the assumed monotonicity of $F/f(c)$, $\bar{A}(c)$ is duly increasing in c. Given $\bar{A}(c)$, we can next explicitly compute $p(c)$ from the constraint,

$$\frac{\bar{A}(c)p(c)^{1-\eta}}{r-\mu} = c + \left(c + \eta\frac{F}{f}(c)\right)^{\lambda}\int_{c}^{c_H}\left(c' + \eta\frac{F}{f}(c')\right)^{-\lambda} dc'. \tag{28}$$

Q.E.D.

Proof of Corollary 1

Note first that the menu of contracts $\bar{A}(c), p(c)$ from proposition 2 defines a parametrized curve that is described by a function $p(\bar{A})$, since $\bar{A}(c)$ is strictly increasing in c.

To prove that $p(\bar{A})$ is downward sloping, since $\bar{A}$ is increasing in c, it is sufficient to show that $p(c)$ is downward sloping. Combining (27) and (28) we write

$$\frac{\lambda}{\lambda-1}\left(\frac{p(c)}{\bar{p}}\right)^{1-\eta} = c\tilde{c}(c)^{-1} + \tilde{c}(c)^{\lambda-1}\int_{c}^{c_H}\tilde{c}(c')^{-\lambda}dc'.$$

with $\tilde{c}(c) = c + \eta\frac{F}{f}(c)$ the virtual cost function. Taking derivatives on both sides, we find that decreasing $p(c)$ is equivalent to

$$(\lambda-1)\tilde{c}(c)^{\lambda}\int_{c}^{c_H}\tilde{c}(c')^{-\lambda}dc' < c. \tag{29}$$

To verify that this inequality holds, note that since $\bar{p} > p(c)$, we have

$$\frac{\lambda}{\lambda-1}\tilde{c}(c) = \frac{\bar{A}(c)\bar{p}^{1-\eta}}{r-\mu} > \frac{\bar{A}(c)p^{1-\eta}}{r-\mu} = c + \tilde{c}(c)^{\lambda}\int_{c}^{c_H}\tilde{c}(c')^{-\lambda}dc',$$

so that

$$\lambda(\tilde{c}(c) - c) + c > (\lambda - 1)\tilde{c}(c)^{\lambda} \int_{c}^{c_H} \tilde{c}(c')^{-\lambda} dc'.$$

Since $\tilde{c}(c) > c$ this implies inequality (29) and we conclude that $p(\bar{A})$ is downward sloping. *Q.E.D.*