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Incentives of a Monopolist for Innovation under Regulatory Threat

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Abstract. In this paper, we investigate whether a natural monopoly with private cost information can reduce the likelihood of regulatory threat by investing, in the ex-ante stage, in cost-reducing R&D to generate process innovations and whether such an investment can yield Pareto gains in welfare. We model the regulatory process using a sequential game where a benevolent regulator makes the first move by announcing the probability that the monopolist will be optimally regulated. The monopolist, hearing this announcement, chooses the optimal level of its R&D investment. We numerically compute the subgame-perfect Nash equilibrium of this game for a wide range of model parameters. Our results show that the monopolist invests more in R&D if the regulatory threat is less certain. Anticipating this response, the regulator makes her threat less certain if she puts more weight on the monopolist's welfare. Moreover, we find that regulation with uncertainty can be Pareto superior to regulation with certainty if the welfare weight of the monopolist is sufficiently, but not extremely, high or if the cost of R&D is sufficiently small.

Keywords: Monopoly; regulatory threat, R&D investment.

JEL Codes: D42; D82; L51; O30.

1 Introduction

Can monopolies have incentives in R&D? Empirical studies (e.g. Sherer, 1967; Blundell et al., 1999) reveal that the answer is 'yes'. There are many explanations consistent with this answer. One is that the firms with high market shares have incentives to innovate pre-emptively, and sometimes even wastefully (Dasgupta and Stiglitz, 1980; Gilbert and Newbery, 1982; Fudenberg et al., 1983). Another explanation is that incentives to hide valuable information can induce firms to use their profits to finance R&D and this is much easier for firms with higher market shares or profits (Bhattacharya and Ritter, 1983). A different angle is proposed by Blundell et al. (1999), who argue that firms with higher market shares invest more in R&D so that they can get a higher valuation on the stock market. In this paper, we suggest another explanation. We argue that monopolies may invest in R&D to reduce the likelihood of regulatory threat. Basically, we consider a natural monopoly with private cost information and show that this monopoly when threatened to be optimally regulated by a public authority (regulator) under the direct-revelation mechanism of Baron and Myerson (BM) (1982), can reduce the likelihood of this threat by investing in cost-reducing innovations and the regulator, anticipating this strategic behavior, can optimally set the likelihood of regulatory threat.

Recently, Saglam (2022) studied whether a natural monopolist facing –under asymmetric information– an external threat to be regulated by the mechanism of BM (1982) can reduce the likelihood of this threat by constraining its price. While Saglam (2022) extends the pioneering work of Glazer and McMillan (1992) who consider the self-regulation problem of a monopolist under symmetric information, we extend both of these works in two directions. First, we differ in the self-regulatory tool available to the monopolist. We assume that the monopolist alleviates the threat of regulation by controlling the amount of R&D investment, instead of constraining its price as in Glazer and McMillan (1992) and Saglam (2022). Second, we change the causality between the external regulatory threat and the self-regulation of the monopolist. Both in Glazer and McMillan (1992) and Saglam (2022), regulation occurs if a bill for regulation is proposed by at least one legislator, while legislators base the probability of regulatory proposal on the expected welfare gain from regulation (net of the cost of proposing a bill) after observing the price chosen by the monopolist before the regulatory phase. Hence, the self-regulation of the monopolist in a given period affects the likelihood of regulation by a public authority in future periods. In contrast, in our model, the likelihood of regulation, i.e. a probability value p, is directly chosen, in the equilibrium of a sequential game, by a benevolent regulator (tasked with maximizing the expected social welfare) who can act as a leader by taking into account the self-regulatory action –the optimal R&D response of the monopolist (the follower) at each value of p. To state it differently, the monopolist chooses –in the models of Glazer and McMillan (1992) and Saglam (2022)– its preventive action (the price constrained in the pre-regulatory period) at such a level that the likelihood of regulation induced by this action maximizes the expected welfare of the monopolist, whereas in our model the likelihood of regulation is determined by the regulator at such a level that the R&D investment induced by this regulatory threat maximizes the expected social welfare. Thus, in Glazer and McMillan (1992) and Saglam (2022) the monopolist appeals to self-regulation (by constraining its price beforehand) to optimally control the likelihood of regulatory threat whereas in our paper the regulator appeals to regulatory threat to optimally impact the R&D investment (or self-regulatory behavior) of the monopolist.

While the idea of a monopolist's self-regulation through R&D investment to alleviate the risk of external regulation is, to the best of our knowledge, novel to our paper, there are previous works that have studied R&D incentives of monopolies when they face external regulation with certainty. (See, for example, Baron and Besanko, 1984; Lewis and Yildirim, 2002; and

Giuseppe and De Vincenti, 2004.) These works generally assume dynamic setups with multi-period monopolies and some of them even assume away the moral-hazard problem.

The closest works to our paper are by Cantner and Kuhn (1999) and Saglam (2019), who study the incentives of a monopolist, in a single-period framework, to invest in cost-reducing innovations whenever it is regulated with certainty under an incentive-compatible mechanism that extends the solution of BM (1982). Cantner and Kuhn (1999) show that when R&D decisions are publicly unobservable and controlled by the monopolist, the optimal regulatory mechanism that has to fully subsidize R&D expenditures cannot assure a second-best (incentive-efficient) outcome even in the absence of a moral-hazard problem since the level of technical progress chosen by the firm becomes too high from the viewpoint of the regulator. They also show that how the regulator can improve the social welfare when she can monitor and control the R&D investments of the monopolist. Saglam (2019) also considers the regulation of a single-period (natural) monopoly with private marginal cost information and R&D possibility, and shows that the R&D expenditures of the monopoly are lower if the regulator is ex-ante aware of R&D activities and ex-post able to monitor these activities than if the regulator is unaware of, and unable to monitor, them. Our paper differs from those of Cantner and Kuhn (1999) and Saglam (2019) in two important aspects. First, unlike in their papers, we assume that the regulator is always aware of the monopolist's R&D technology and that she can fully monitor its R&D investment. Second, and more distinctively, the monopolist has an additional incentive for cost-reducing innovations in our paper. Both Cantner and Kuhn (1999) and Saglam (2019) assume that external regulation will occur with certainty, leaving no role for the self-regulation of the monopolist. Thus, the monopolist's incentive for cost-reducing R&D is only to increase the information rent that will be provided by a given incentive-compatible regulatory mechanism. However, in our work the external regulation may occur with uncertainty and this uncertainty presents an additional incentive for innovation once the monopolist realizes that it can alleviate the regulatory threat by making cost-reducing R&D investments.

We assume that the regulatory process consists of two stages: the ex-ante stage and the interim stage. In the ex-ante stage, the monopolist has not learned its marginal cost yet. In this stage, the regulator picks a probability value and announces that the monopolist will be regulated in the interim stage with this probability and under the optimal regulatory mechanism of BM (1982). The monopolist, hearing this announcement, chooses the optimal level of R&D investment maximizing its expected welfare under the regulatory threat it faces. In the following (interim) stage, the monopolist privately learns its cost parameter. Then, the randomization associated with the regulatory threat is realized. If the outcome requires regulatory action, the monopolist is regulated in accordance with the BM (1982) mechanism, under which the monopolist reveals its private cost information in return for some information rent. But, if the outcome of the randomization implies no regulatory action, the monopolist is allowed to freely enjoy its monopoly profits.

The described regulatory process involves a strategic game played by the monopolist and the regulator in the ex-ante stage. The regulator picks and announces a probability of regulation and the monopolist, after hearing this announcement, decides on its R&D level. We assume that the regulator is capable to solve this sequential game by backward induction. That is, she can calculate for each value of the probability of regulation, the monopolist's optimal R&D response and the expected social welfare induced by it. This calculation allows the regulator to determine the equilibrium probability value under which the expected social welfare, induced by the monopolist's R&D response, is maximized.

The strategy pair involving the monopolist's optimal R&D response schedule (calculated at each value of the probability of regulation) and the socially-optimal probability of regulation forms a subgame-perfect Nash equilibrium (SPNE) for the described sequential game. We numerically compute this equilibrium for a rich set of parameter values and make several comparative statics. Our main results suggest that the monopolist invests more in R&D if the regulatory threat is less certain. Anticipating this behavior, the regulator makes her threat less certain if the monopolist becomes more favored by the social welfare function. Moreover, we find that regulation with uncertainty can be Pareto superior to regulation with certainty if the welfare weight of the monopolist is sufficiently, but not extremely, high or if the cost of R&D is sufficiently small.

The remainder of the paper is organized as follows: Section 2 introduces our theoretical model, Section 3 presents our computational results, and Section 4 concludes.

2 The Model

We consider a monopolistic industry where a single good can be produced subject to the cost function

$$C(q, \theta) = \theta q \;\text{ if } q > 0 \;\text{ and }\; C(0, \theta) = 0. \tag{1}$$

Above, the variable $q \geq 0$ denotes the output of the monopolist and the parameter $\theta \in [0, a)$ denotes its marginal cost of production. (We have assumed away fixed costs to simplify the analysis.) The inverse demand function facing the monopolist is given by

$$P(q) = a - q, \tag{2}$$

where $a > 0$ is constant.

The monopolist is threatened to be regulated by a public authority (simply the regulator) that knows everything about the described industry excluding the marginal cost parameter θ. Nevertheless, the regulator has the prior belief that the parameter θ is uniformly distributed on the interval $[0, a)$. We denote this belief by the probability density function $f^0(\theta)$, satisfying $f^0(\theta) = 1/a$ if $\theta \in [0, a)$ and $f^0(\theta) = 0$ otherwise.

The monopolist has access to an R&D technology. This technology decreases the support of θ from $[0, a)$ to $[0, a - x)$ for a given level of R&D investment $x \in [0, a)$ if the monopolist bears the corresponding R&D cost $K(x)$. We assume that for any $x \in [0, a)$,

$$K(x) = \frac{c_0\, x}{a - x} \tag{3}$$

where $c_0 = K(a/2) > 0$ is constant. Notice that the R&D cost function $K(x)$ is increasing in x. Moreover, $K(0) = 0$, i.e., there are no fixed costs of R&D, and $\lim_{x \to a} K(x) = \infty$, i.e., innovations reducing the marginal cost to zero with certainty are infinitely costly. Here, we also assume that R&D investment of the monopolist is fully observable to the regulator. Moreover, it is common knowledge that the regulator, after observing an R&D investment of size x, will update her prior belief $f^0(\theta)$ to the posterior belief $f(\theta|x)$ in accordance with the Bayes theorem. Thus, the regulator's posterior belief would be a uniformly distributed probability density function satisfying $f(\theta|x) = 1/(a - x)$ if $\theta \in [0, a - x)$ and $f(\theta|x) = 0$ otherwise. Notice also that $f(\theta, 0) = f^0(\theta)$ for every θ.

The regulatory process consists of two stages, called the ex-ante and interim stages. In the ex-ante stage, the monopolist does not know yet its marginal cost θ. In this stage, the regulator picks a real number, p, from the interval $[0, 1]$ and announces that in the interim stage the monopolist will be regulated with probability p and in accordance with the optimal mechanism of BM (1982) modified under the regulator's posterior beliefs. The monopolist, hearing this announcement, decides on the optimal value of $x \in [0, a)$, i.e., the level of *R&D* investment maximizing its expected welfare (that we will define later) under the threat of regulation implied by the probability p.

In the second (interim) stage, the monopolist privately learns its cost parameter θ. Then the randomization corresponding to the regulatory probability p is realized. If the outcome of this randomization requires regulatory action, the monopolist is regulated, as it was already informed, under the optimal mechanism of BM (1982), requiring the monopolist to reveal its private cost information in return for some information rent calculated at the output schedule maximizing the expected social welfare under the regulator's posterior belief $f(\theta|x)$. On the other hand, if the outcome of the randomization implies no regulatory action, the monopolist is allowed to freely enjoy its monopoly profits.

To determine the monopolist's R&D choice in the above regulatory process, we have to calculate the expected welfare of the monopolist for each pair of x and p in their assumed domains. This expected welfare is a weighted average of its expected monopoly profit obtained in the absence of regulation and its expected profit (information rent) obtained in the case of regulation according to the BM mechanism. Below, we will calculate these two profits separately.

Notice that the marginal cost of production, θ, is unknown to the monopolist in the ex-ante stage. But, if it were known, then the monopolist could calculate its actual unregulated profit

$$\pi(q, \theta, x) = P(q)q - \theta q = (a - \theta)q - q^2 - K(x) \tag{4}$$

for any output choice $q \geq 0$ and R&D choice $x \in [0, a)$ that would be sunk in the interim stage. It is easy to see that the monopolist would maximize $\pi(q, \theta, x)$ at the output level $q^m(\theta, x) = (a - \theta)/2$ to enjoy the profit $\pi^m(\theta, x) \equiv \pi(q^m(\theta), \theta, x) = (a-\theta)^2/4 - K(x)$. The unregulated monopolist's expected profit in the interim stage is the expected value of $\pi^m(\theta, x)$ under the beliefs $f(\theta|x)$. We can calculate this expected profit as

$$E[\pi^m(\theta, x)] \;\; = \;\; \int_0^{a-x} \pi^m(\theta, x) f(\theta|x) d\theta$$

$$
\begin{aligned}
&= \int_0^{a-x} \frac{(a-\theta)^2}{4} \frac{1}{a-x} d\theta - K(x) \\
&= \frac{a^3 - x^3}{12(a-x)} - K(x) \qquad (5)
\end{aligned}
$$

for any $x \in [0, a)$. Notice that the actual welfare of consumers will be $CW^m(\theta) = \int_0^{q^m(\theta)} P(y)dy - P(q^m(\theta))q^m(\theta)$ if the monopolist produces $q^m(\theta)$. So, the expected welfare of consumers will be

$$
\begin{aligned}
E[CW^m(\theta)] &= \int_0^{a-x} d\theta f(\theta|x) \left(\int_0^{q^m(\theta)} P(y)dy - P(q^m(\theta))q^m(\theta) \right) \\
&= \int_0^{a-x} \frac{(a-\theta)^2}{8} \frac{1}{a-x} d\theta = \frac{a^3 - x^3}{24(a-x)}. \qquad (6)
\end{aligned}
$$

We assume that the expected social welfare is a weighted sum of the expected welfares of consumers and the monopolist, given by

$$
SW^{m,e}(\theta) = CW^{m,e}(\theta) + \alpha\, \pi^{m,e}(\theta) = \frac{(1+2\alpha)(a^3 - x^3)}{24(a-x)} - \alpha K(x), \quad (7)
$$

where α is a constant weight parameter in $[0, 1]$.

We will now calculate the expected profit obtained by the monopolist if it is regulated with certainty in the interim stage according to the BM (1982) mechanism. This mechanism is a direct-revelation mechanism that requires the monopolist to report its marginal cost parameter θ and that eliminates any incentive for untruthful reporting. We denote this mechanism, obtained with some minor modifications from the BM (1982) mechanism, by $\langle p(.), q(.), r(.), s(.) \rangle$. At the monopolist's cost report $\tilde{\theta}$, $p(\tilde{\theta})$ and $q(\tilde{\theta})$ respectively denote the price and the output which are consistent, i.e., $p(\tilde{\theta}) = a - q(\tilde{\theta})$, $r(\tilde{\theta})$ denotes the probability that the monopolist is permitted to operate, and $s(\tilde{\theta})$ denotes the expected subsidy consumers pay to guarantee truthful cost revelation. Given the described mechanism, if the monopolist with the actual marginal cost θ reports it as $\tilde{\theta}$, then for any $x \in [0, a)$, it gains the profit

$$\pi(\tilde{\theta}, \theta, x) = \pi^{NS}(\tilde{\theta}, \theta, x) - K(x), \tag{8}$$

where $\pi^{NS}(\theta, \theta, x)$ denotes the non-sunk part of its profit, satisfying

$$\pi^{NS}(\tilde{\theta}, \theta, x) = [p(\tilde{\theta})q(\tilde{\theta}) - \theta q(\tilde{\theta})]r(\theta) + s(\tilde{\theta}). \tag{9}$$

(Above, we suppress the dependence of $p(\theta), q(\theta), r(\theta)$, and $s(\theta)$ on x, for notational clarity and simplicity.)

The described mechanism is feasible if the monopolist's non-sunk profit π^{NS} is incentive-compatible and individually rational. The first condition requires

$$\pi^{NS}(\theta, x) \equiv \pi^{NS}(\theta, \theta, x) \geq \pi^{NS}(\tilde{\theta}, \theta, x) \tag{10}$$

for all $\theta, \tilde{\theta} \in [0, a - x)$ and $x \in [0, a)$, whereas the second condition requires

$$\pi^{NS}(\theta, x) \geq 0 \tag{11}$$

for all $\theta \in [0, a - x)$ and $x \in [0, a)$. Notice that this individual rationality condition assumes that the regulator does not subsidize (reimburse the 'sunk' costs of) the R&D investment of the monopolist when it is regulated. We have implicitly assumed this in the case of no regulation, as well.

By the reasoning of BM (1982), the incentive-compatibility condition holds only if the schedule $q(.)$ is non-increasing on $[0, a - x)$ and the monopolist's non-sunk profit is given by

$$\pi^{NS}(\theta, x) = \int_{\theta}^{a-x} q(y)r(y)dy + \pi^{NS}(a - x, x). \tag{12}$$

This requires that the subsidy given to the monopolist must be equal to

$$\begin{aligned} s(\theta) &= \pi^{NS}(\theta, x) - [p(\hat{\theta})q(\hat{\theta}) - \theta q(\hat{\theta})]r(\theta) \\ &= \int_{\theta}^{a-x} q(y)r(y)dy + \pi^{NS}(a - x, x) - [p(\hat{\theta})q(\hat{\theta}) - \theta q(\hat{\theta})]r(\theta). \end{aligned} \tag{13}$$

Then, for any $x \in [0, a)$ and $\theta \in [0, a - x)$, we can calculate the actual welfare of consumers by subtracting the subsidy paid to the monopolist from the consumer surplus to obtain

$$\begin{aligned} CW(\theta, x) &= \left[\int_0^{q(\theta)} (a - x)dx - p(\theta)q(\theta)\right] r(\theta) - s(\theta) \\ &= \left[\int_0^{q(\theta)} (a - x)dx - \theta q(\theta)\right] r(\theta) - \pi^{NS}(\theta, x) \end{aligned} \quad (14)$$

Finally, given any $\alpha \in (0, 1)$, we define the actual social welfare

$$SW(\theta, x) = CW(\theta, x) + \alpha\pi(\theta, x). \quad (15)$$

The regulator's problem is to select a feasible mechanism that maximizes, under her posterior beliefs, the expected social welfare given by

$$SW^e(x) \equiv \int_0^{a-x} SW(\theta, x) f(\theta|x) d\theta$$

$$= \int_0^{a-x} \left(\left[\int_0^{q(\theta)} (a - x)dx - \theta q(\theta)\right] r(\theta) - (1 - \alpha)\pi^{NS}(\theta, x)\right) f(\theta|x) d\theta$$
$$-\alpha K(x). \quad (16)$$

Above, the weight $1 - \alpha$, whenever $\alpha \neq 1$, implies a social welfare loss, possibly caused by distortionary taxation on consumers to finance information rent of the monopolist.

Equations (12) and (16) together imply that any mechanism that maximizes $SW^e(x)$ must set $\pi^{NS}(a - x, x) = 0$. Then, one can easily verify that the optimal mechanism, which slightly modifies the BM (1982) mechanism, will be $\langle p^{BM}(.), q^{BM}(.), r^{BM}(.), s^{BM}(.)\rangle$ that satisfies

$$p^{BM}(\theta) = \theta + (1 - \alpha)\frac{F(\theta|x)}{f(\theta|x)} = (2 - \alpha)\theta \quad (17)$$

$$q^{BM}(\theta) = a - (2-\alpha)\theta \tag{18}$$

$$r^{BM}(\theta) = \begin{cases} 1 & \text{if } \theta \leq \theta^* \equiv \min\{a-x, a/(2-\alpha)\} \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

$$\begin{aligned} s^{BM}(\theta) &= \int_\theta^{a-x} q^{BM}(y) r^{BM}(y) dx \\ &\quad + [\theta q^{BM}(\theta) - p^{BM}(\theta) q^{BM}(\theta)] r^{BM}(\theta) \end{aligned} \tag{20}$$

for all $\theta \in [0, a-x)$ and $x \in [0, a)$.

Notice that the optimal price $p^{BM}(\theta)$ exceeds the marginal cost θ by an information markup $(1-\alpha)F(\theta|x)/f(\theta|x) = (1-\alpha)\theta$ in order to optimally limit the regulated output schedule $q^{BM}(.)$ and consequently the information rent of the monopolist $\int_\theta^{a-x} q^{BM}(y) r^{BM}(y) dx$. Also, notice that the R&D investment x does not affect the regulated price and output schedules. On the other hand, x may affect both r^{BM} and $s^{BM}(\theta)$. Equation (19) shows that the highest value of the marginal cost, θ^*, at which the regulated monopolist will be allowed to produce, is affected by x if only if x is so high that $a - x < a/(2-\alpha)$. Therefore, r^{BM} is nonincreasing in x. Also, it is easy to see from (20) that the subsidy $s^{BM}(\theta)$ is reduced at each θ when the monopolist increases its R&D investment x.

Under the mechanism characterized above, we can calculate, for any $x \in [0, a)$, the monopolist's actual welfare as

$$\begin{aligned} \pi^{BM}(\theta, x) &= \int_\theta^{\theta^*(\alpha)} q^{BM}(y) dy - K(x) \\ &= \begin{cases} a(k-\theta) - (2-\alpha)\dfrac{(k^2-\theta^2)}{2} - K(x) & \text{if } a - x \leq \dfrac{a}{2-\alpha} \\ \left(\dfrac{2-\alpha}{2}\right)\theta^2 - a\theta + \dfrac{a^2}{2(2-\alpha)} - K(x) & \text{if } a - x > \dfrac{a}{2-\alpha} \end{cases} \end{aligned} \tag{21}$$

if $\theta \in [0, \theta^*(\alpha))$ and $\pi^{BM}(\theta, x) = 0$ otherwise. Likewise, for any $x \in [0, a)$, the actual consumer welfare can be calculated as

$$\begin{aligned} CW^{BM}(\theta, x) &= \left[\int_0^{q^{BM}(\theta)} (a-y)dy - \theta q^{BM}(\theta)\right] r^{BM}(\theta) - \pi^{BM}(\theta, x) + K(x) \\ &= \left((a-\theta)\left[a-(2-\alpha)\theta\right] - \frac{1}{2}\left[a-(2-\alpha)\theta\right]^2\right) r^{BM}(\theta) \\ &\quad -\pi^{BM}(\theta, x) + K(x) \end{aligned} \tag{22}$$

if $\theta \in [0, a-x)$ and $CW^{BM}(\theta, x) = 0$ otherwise. In the ex-ante stage, consumers and the monopolist know the expected (but not the actual) values of $\pi^{BM}(\theta, x)$ and $CW^{BM}(\theta, x)$ under the posterior belief $f(\theta|x)$, which is formed after the regulator observes the monopolist's R&D level x. We can calculate these expected welfares as

$$\begin{aligned} E[\pi^{BM}(\theta, x)] &= \int_0^{a-x} \pi^{BM}(\theta, x) r^{BM}(\theta) f(\theta|x) d\theta \\ &= \begin{cases} a\dfrac{(a-x)}{2} - (2-\alpha)\dfrac{(a-x)^2}{3} - K(x) & \text{if } a-x \leq \dfrac{a}{2-\alpha} \\ \dfrac{a^3}{6(a-x)(2-\alpha)^2} - K(x) & \text{if } a-x > \dfrac{a}{2-\alpha} \end{cases} \end{aligned} \tag{23}$$

and

$$\begin{aligned} E[CW^{BM}(\theta, x)] &= \int_0^{a-x} CW^{BM}(\theta, x) r^{BM}(\theta) f(\theta|x) d\theta \\ &= \begin{cases} -\dfrac{a^2}{2} + ax + \dfrac{(4-\alpha^2)}{6}(a-x)^2 & \text{if } a-x \leq \dfrac{a}{2-\alpha} \\ \dfrac{2(1-\alpha)a^3}{6(a-x)(2-\alpha)^2} & \text{if } a-x > \dfrac{a}{2-\alpha} \end{cases} \end{aligned} \tag{24}$$

respectively. Consequently, the expected social welfare under the BM mechanism can be calculated as

$$
\begin{aligned}
E[SW^{BM}(\theta, x)] &= E[CW^{BM}(\theta, x)] + \alpha E[\pi^{BM}(\theta, x)] \\
&= \begin{cases} \varphi(x) - \alpha K(x) & \text{if } a - x \leq \dfrac{a}{2-\alpha} \\[2ex] \dfrac{a^3}{6(a-x)(2-\alpha)} - \alpha K(x) & \text{if } a - x > \dfrac{a}{2-\alpha} \end{cases}
\end{aligned} \tag{25}
$$

where

$$
\varphi(x) = \frac{a^2}{2} - (2-\alpha)\frac{a(a-x)}{2} + \frac{(2-\alpha)^2}{6}(a-x)^2. \tag{26}
$$

Notice that all expected welfares depend on the R&D level x. So, for convenience, we will use the notation $Z^{m,e}(x) \equiv E[Z^m(\theta, x)]$ and $Z^{BM,e}(x) \equiv E[Z^{BM}(\theta, x)]$ for any $Z \in \{\pi, C, SW\}$.

Recall that the BM mechanism is implemented with probability p in the interim stage. Thus, for any $p \in [0, 1]$ and $x \in [0, a)$, the expected producer welfare, the expected consumer welfare, and the expected social welfare, whenever they are calculated in the ex-ante stage, will be

$$
PW^e(p, x) = p\, \pi^{BM,e}(x) + (1-p)\, \pi^{m,e}(x), \tag{27}
$$

$$
CW^e(p, x) = p\, CW^{BM,e}(x) + (1-p)\, CW^{m,e}(x) \tag{28}
$$

$$
SW^e(p, x) = p\, SW^{BM,e}(x) + (1-p)\, SW^{m,e}(x) \tag{29}
$$

respectively.

Now, we turn back to the sequential game played by the monopolist and the regulator in the ex-ante stage. We should recall that the regulator moves first by choosing and announcing the probability of regulation p and then the monopolist, hearing this announcement, chooses its R&D level x. Being aware of the potential effect of p on x, the regulator can determine its equilibrium strategy by backward induction. The regulator can first compute for each value of $p \in [0,1]$, the monopolist's optimal R&D level $x(p)$ by solving the problem

$$x(p) = \text{argmax}_{x' \in [0,a)} \; PW^e(p, x'). \tag{30}$$

Next, for any value of $p \in [0,1]$, the regulator can calculate the expected social welfare $SW^e(p, x(p))$ induced by the monopolist's R&D choice $x(p)$ in response to the regulatory threat implied by p. Hence, the regulator can determine the optimal probability of regulation, p^*, that maximizes the expected social welfare, i.e.,

$$p^* = \text{argmax}_{p \in [0,1]} \; SW^e(p, x(p)). \tag{31}$$

The strategy pair involving the probability p^* and the R&D choice $x(p)$ for all $p \in [0,1]$ forms a subgame-perfect Nash equilibrium (SPNE) for the sequential game. Once p^* is determined by the regulator in this game, the monopolist optimally responds with the R&D investment $x^* = x(p^*)$. At the pair of actions (p^*, x^*), we can then calculate the expected equilibrium welfares of the producer, consumers, and the society as $PW^{e,*} \equiv PW^e(p^*, x^*)$, $CW^{e,*} \equiv SW^e(p^*, x^*)$, and $SW^{e,*} \equiv SW^e(p^*, x^*)$, respectively. Note that the equilibrium actions p^* and x^* as well as the expected welfare distribution induced by them all depend on the model parameters α, c_0, and a.

In the next section, we will explore how changes in these parameters may affect the solution (p^*, x^*) of the regulatory game and the corresponding welfare distribution in the industry.

3 Computational Results

We conduct our numerical computations using GAUSS version 3.2.34. The software code and the data generated are available upon request from the author. In our first set of computations, presented in Section 3.1, we analyze how the probability of regulation affects the optimal R&D choice of the monopolist and the welfare distribution in the industry under several values of α, the weight assigned by the social welfare function to the monopolist's welfare. We also show graphically how the regulator chooses the socially-optimal probability of regulation using backward induction. After gaining insight into how an equilibrium (SPNE) is formed, we will calculate and analyze the equilibrium of our model for different values of the welfare weight (α) in Section 3.2 and for different values of the R&D cost parameter (c_0) in Section 3.3.

3.1 Calculating the R&D Response $x(p)$ and the Implied Welfare Distribution

For the computations in this subsection, we set $a = 1$ and $c_0 = 0.01$ and consecutively set the parameter α to one of the three values in $\{0, 0.5, 1\}$. The setting $\alpha = 0$ means that the social welfare function puts zero weight on the expected welfare of the monopolist. In that case, the subsidy paid by consumers to the monopolist –to ensure truthful cost revelation under the BM (1982) mechanism– becomes extremely distortionary. In the absence of R&D possibility, the setting $\alpha = 0$ leads to an utterly inequitable regulatory outcome where the total economic surplus (the sum of the consumer and producer welfares) as well as the producer welfare attain their lowest levels whereas the consumer welfare attains its highest level. One can check these using equations (23) and (24). If the monopolist were to choose $x = 0$, then the expected producer welfare, $V/4$, would become the half of the expected consumer welfare, $V/2$, where $V = a^2/6$ is the maximal expected (economic) surplus in the industry independent of the value of α. The economic surplus would then be equal to its minimum level of $3V/4$.

The setting $\alpha = 0.5$ corresponds to the egalitarian case where the expected producer and consumer welfares are equalized at the level of $4V/9$

when $x = 0$. On the other hand, $\alpha = 1$ corresponds to another case of utter inequity where the expected consumer welfare becomes zero and the expected producer welfare becomes equal to the maximal expected surplus (V) whenever $x = 0$. One should also notice that when $x = 0$, a higher value for α increases the expected producer welfare and decreases the expected consumer welfare. In this section, we will explore the effect of α on the expected welfare distribution whenever x is optimally determined by the monopolist under regulatory threat.

Using the assumed parameter values, we numerically compute, for each value of the probability regulation $p \in [0, 1]$, the optimal R&D investment $x(p)$ of the monopolist and the implied welfare distribution in the industry. Our results illustrated in Figures 1-3 show that the presence of R&D always increases the expected welfare of both the monopolist and consumers irrespective of the probability of regulation. (Notice that in panels (ii)-(iv) we also illustrate by black colored curves the welfare distribution obtained in the absence of R&D possibility, i.e., the case of $x(p) = 0$ for all p). Moreover, we find that the monopolist's R&D response $x(p)$, drawn in panel (i), is always decreasing in p. That is, the monopolist finds it optimal to invest less in R&D if the probability of regulation is higher.

In panel (ii) of Figures 1-3, we portray the expected producer welfare, $PW^e(p, x(p))$, at each value of p. When $\alpha = 0$ as in Figure 1, we find that $PW^e(p, x(p))$ is decreasing in p, implying that the expected producer welfare attains its maximum if the monopolist is not regulated ($p = 0$) and responds with the highest R&D on its optimal response schedule. The same result also arises when $\alpha = 0.5$, as we can see in Figure 2. When $\alpha = 1$, the effect of p on the expected producer welfare becomes non-monotonic, as illustrated in Figure 3. The expected producer welfare decreases up to $p = 0.34$ and then increases up to $p = 1$, where it attains its maximum.

Figure 1. Expected Welfares Calculated at the R&D Response $x(p)$

$(\alpha = 0, \;\; a = 1, \;\; c_0 = 0.01)$

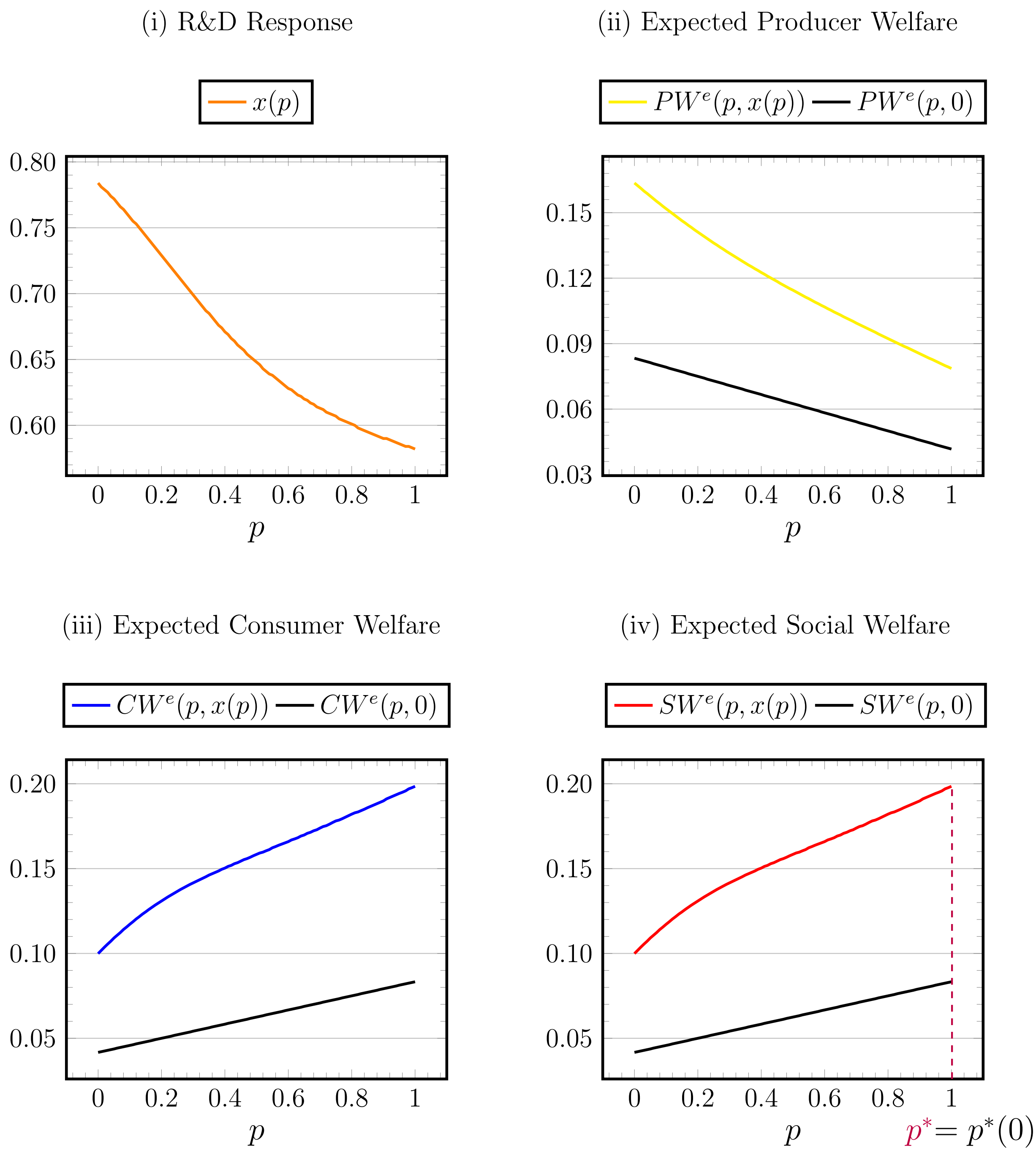


Figure 2. Expected Welfares Calculated at the R&D Response $x(p)$

$(\alpha = 0.5, \;\; a = 1, \;\; c_0 = 0.01)$

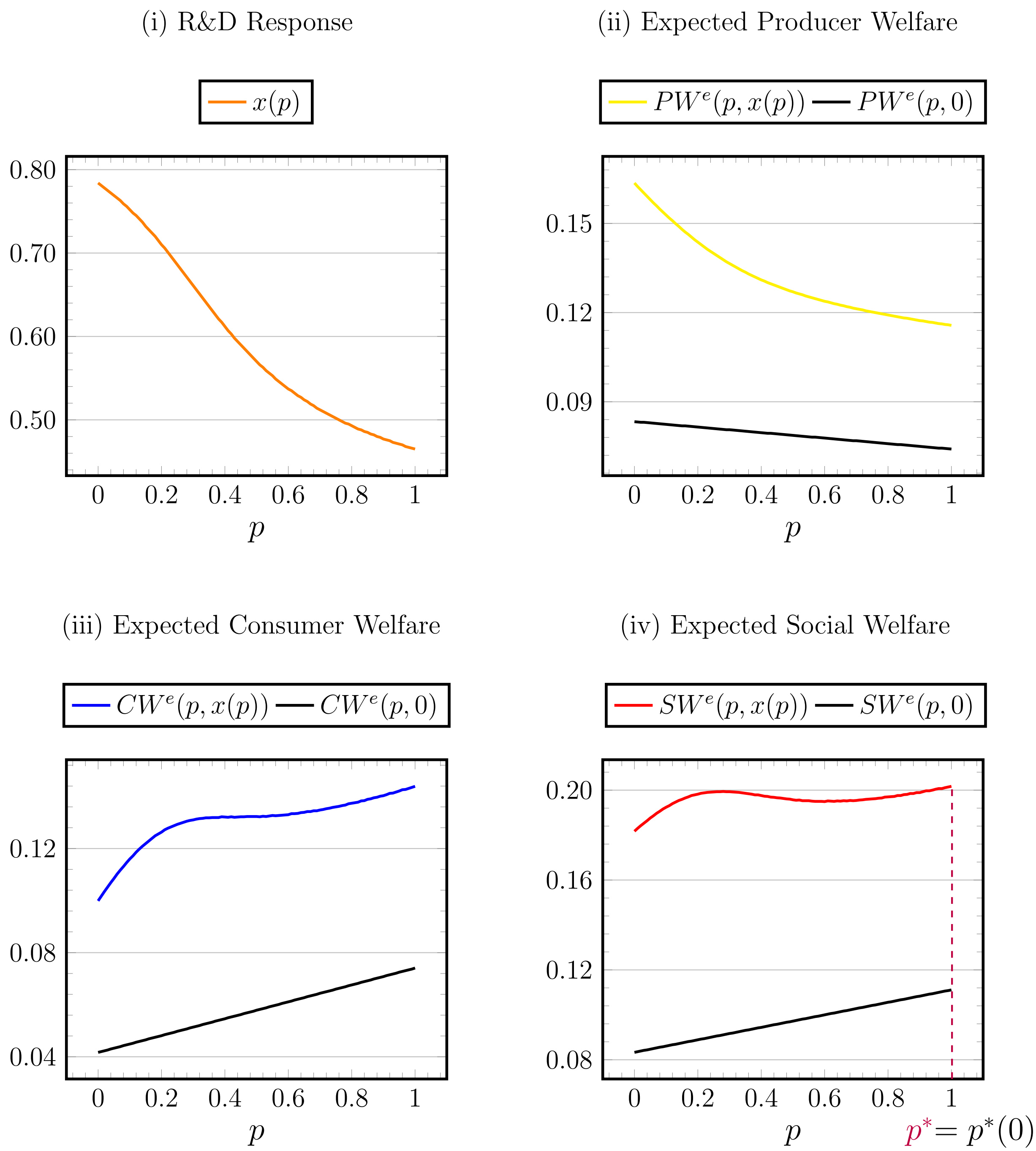
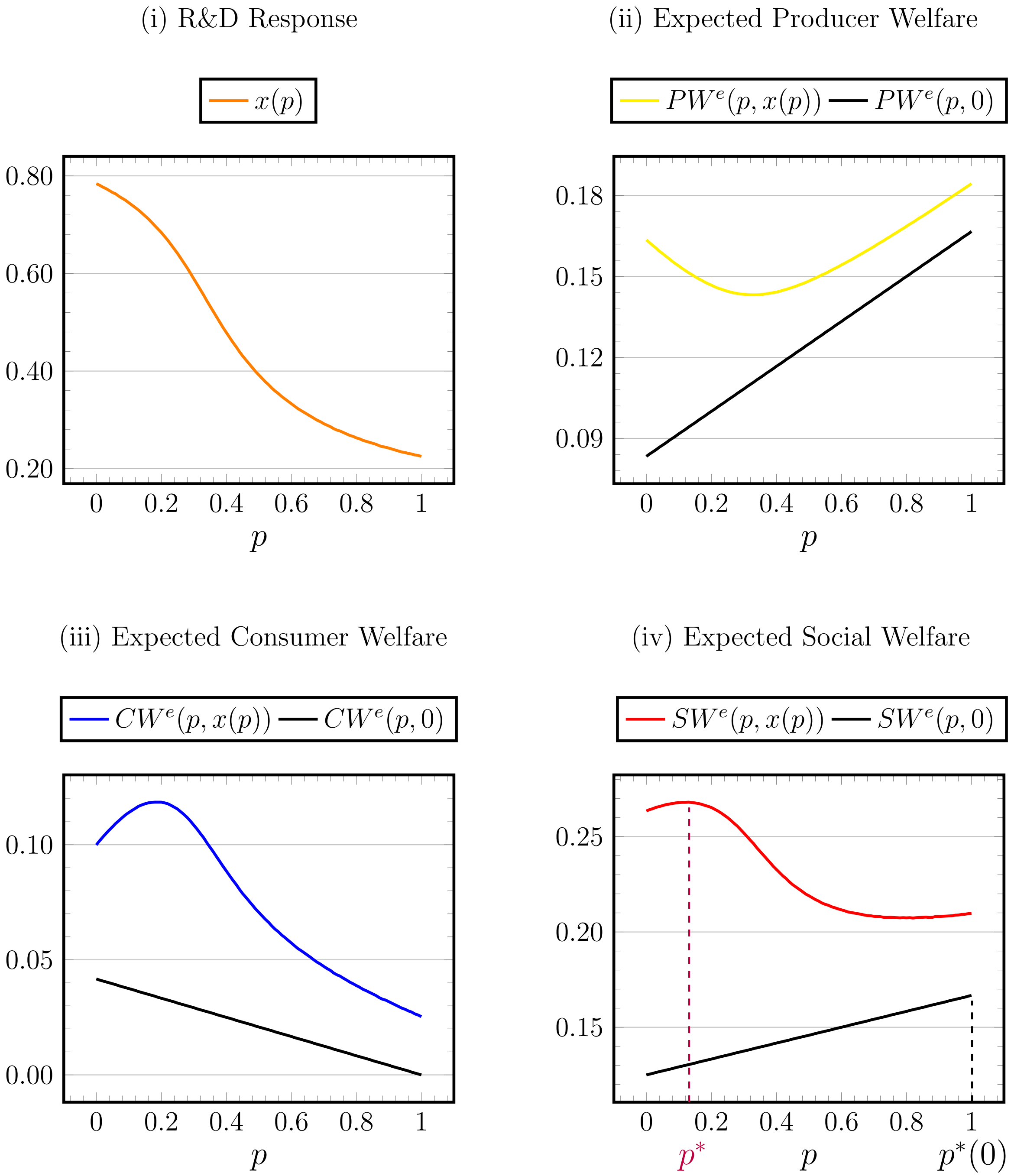


Figure 3. Expected Welfares Calculated at the R&D Response $x(p)$

$(\alpha = 1,\ \ a = 1,\ \ c_0 = 0.01)$



Result 1. *For any $\alpha \in \{0, 0.5, 1\}$, the optimal R&D response of the monopolist, $x(p)$, is decreasing in p. Moreover, irrespective of R&D possibility, the monopolist ex-ante prefers to be unregulated ($p = 0$) when $\alpha = 0$ or $\alpha = 0.5$ and to be regulated with certainty ($p = 1$) when $\alpha = 1$.*

The effect of α on the expected consumer and social welfare depends on the size of α. If $\alpha = 0$, both CW^e and SW^e are always increasing in p, as graphed in the last two panels of Figure 1. This is always true regardless of whether R&D is possible. Thus, the socially-optimal probability of regulation occurs at $p^* = 1$, where SW^e attains its maximum. Notice that $p^* = 1$ is the worse probability for the monopolist, which can attain its highest expected profits always when it is unregulated ($p = 0$). When $\alpha = 0.5$, both consumer and social welfare rise with p in the absence of R&D possibility. When the monopolist can engage in R&D, however, the consumer welfare becomes nondecreasing in p while the expected social welfare becomes non-monotonically changing in p, having a local maximum at $p = 0.28$ and a global maximum at $p = 1$. Thus, the regulator finds it socially optimal to regulate the monopolist with certainty, as in the case of $\alpha = 0$. Notice that $p = 1$ is the best probability for consumers as well, but the worst probability for the monopolist.

Result 2. *If $\alpha = 0$ or $\alpha = 0.5$, then the regulator finds it socially optimal to choose the probability of regulation as 1, irrespective of R&D possibility.*

If $\alpha = 1$ as in Figure 3, then CW^e and SW^e become hump-shaped whenever the monopolist can optimally invest in R&D. The optimal probability of regulation that maximizes SW^e then occurs at $p^* = 0.13$. At this probability, the monopoly becomes worse off than it would be both when it is unregulated ($p = 0$) and when it is regulated with certainty ($p = 1$), as illustrated in panel (ii). On the other hand, when the monopolist cannot invest in R&D,

the expected social welfare is increasing in p, as in the cases of $\alpha = 0$ and $\alpha = 0.5$.

Result 3. *Let $\alpha = 1$. Then, the regulator finds it socially optimal (i) to regulate the monopolist with a very low probability ($p^* = 0.13$) if the monopoly can optimally invest in R&D and (ii) to leave the monopolist unregulated if it cannot invest in R&D.*

Notice the difference between the Results 2 and 3 stems from the fact that under the absence of any R&D investment, the expected welfare of the monopolist when it is regulated with certainty exceeds the expected welfare of consumers if and only if α is above 0.5. In fact, the whole expected surplus accrues to the monopolist as information rent when $\alpha = 1$. However, as panel (i) of Figure 3 suggests that the monopolist's incentive to innovate becomes very small when $p = 1$, i.e. when regulation is certain. (Notice that the monopolist's R&D sharply falls from 0.78 at $p = 0$ to 0.23 at $p = 1$.) Since the benefit of R&D to consumers turns out to be far above its benefit to an unregulated monopolist, the regulator finds it optimal to induce the monopolist to invest in a high level of R&D by reducing the probability of regulation dramatically.

3.2 The Effects of α on the SPNE Outcomes

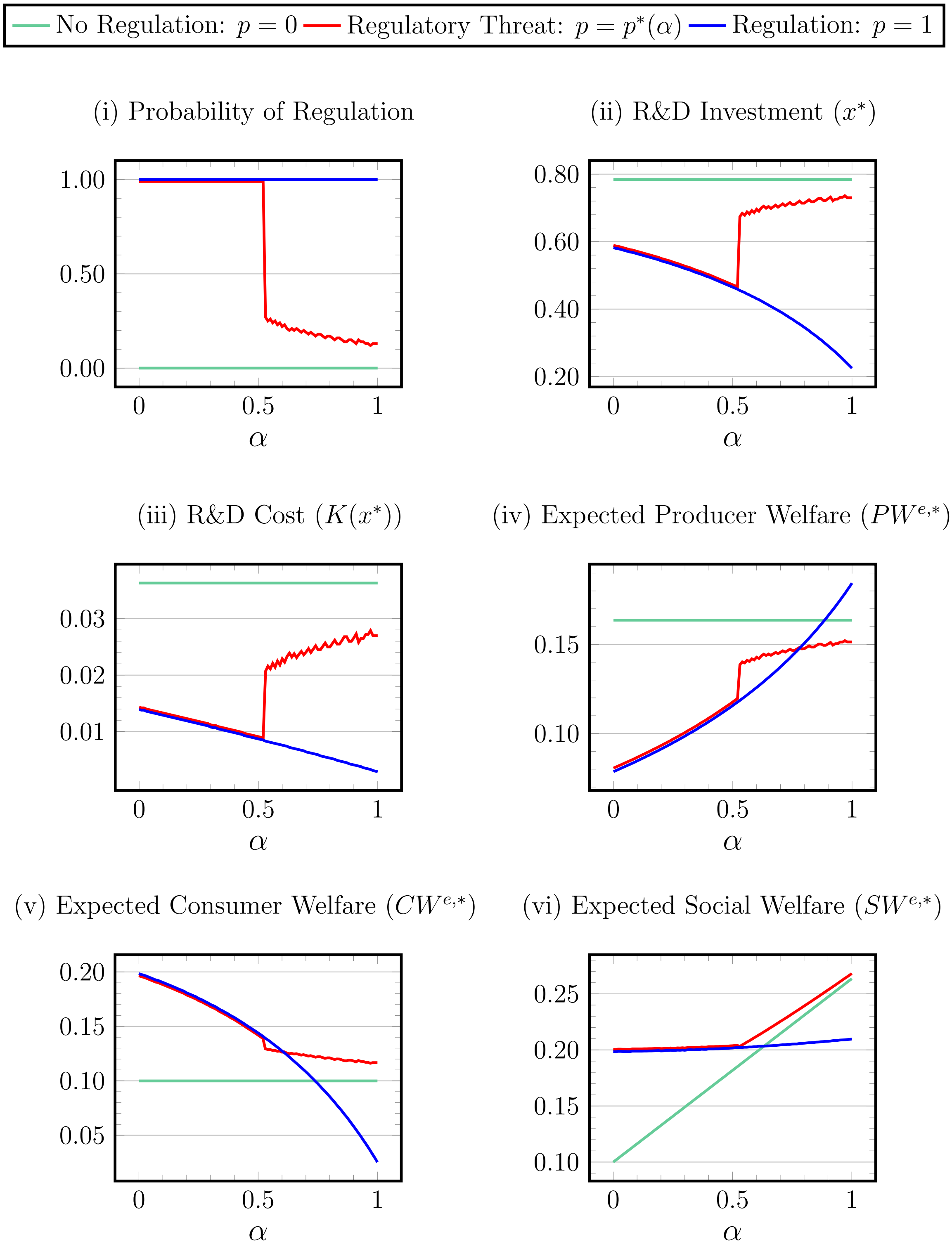
In the previous subsection, we have illustrated graphically how one can calculate the socially-optimal probability of regulation p^* and how this probability and the induced welfare distribution are affected when α jumps first from 0 to 0.5 and then from 0.5 to 1. Now, we will explore whether we can extend our results on these special α values to a larger set. To this aim, we vary α inside the set $\{0.00, 0.01, \ldots, 1.00\}$ with increments of 0.01, while retaining our assumption that $a = 1$ and $c_0 = 0.01$. We portray our computational results in Figure 4. In panel (i), we calculate the optimal probability of regulation p^* at each percentile value of α. We observe that the optimal probability of regulation, p^*, is always 1 if α is smaller than 0.53. When $\alpha = 0.53$, p^* drops to 0.27 and tends to decrease while α becomes larger. Indeed, p^* attains its lowest level at 0.13 when α becomes 1.

Result 4. *Leaving the monopolist unregulated cannot be optimal at any value of α. It is optimal to regulate the monopolist with certainty if $\alpha \leq 0.52$ and with uncertainty otherwise. Moreover, the optimal probability of regulation, p^*, is decreasing in α if $\alpha > 0.52$.*

In panel (ii), we draw the monopolist's equilibrium R&D (in response to the optimal probability of regulation) as a function of α. Notice that the green curve shows the R&D investment when the monopolist is unregulated ($p = 0$) and the blue curve shows the R&D investment when it is regulated with certainty ($p = 1$). As α increases to 0.53, x^* on the red curve decreases, then jumps up at $\alpha = 0.53$ and continuously rises with α. When α reaches 1, x^* is still below the level attained in the case of no regulation since the socially-optimal probability of regulation ($p^* = 0.13$) is realized at a level higher than zero.

Result 5. *For all percentile values of α, the monopolist's equilibrium R&D attains its highest level when the monopolist is unregulated. If $\alpha \leq 0.52$, the optimal regulatory threat is always certain and the equilibrium R&D is decreasing in α. If $\alpha \geq 0.53$, then the equilibrium R&D is always higher when regulation is uncertain than it is certain. Also, when $\alpha \geq 0.53$, the equilibrium R&D is increasing in α if the regulation is socially optimal, and hence uncertain, and decreasing in α if the regulation is certain.*

Figure 4. SPNE Outcomes For Different Values of α
($a = 1,\ \ c_0 = 0.01$)



Panel (iii) of Figure 4 shows that as α changes the R&D cost $K(x^*)$ follows the path of x^*. This is expected since $K(x^*)$ is increasing in x^*. Panel (iv) illustrates the effect of α on the expected producer welfare PW^e. Notice that PW^e attains a constant level of 0.16 when the monopolist is not regulated (the green curve). On the other hand, PW^e is always increasing in α if the monopolist is regulated with certainty (the blue curve) and also if it is regulated with uncertainty (the red curve). A closer look allows us to observe the following result.

Result 6. *The monopolist's expected welfare is always lower when it is regulated with uncertainty than when it is unregulated. If α is between 0.53 and 0.78, the monopolist ex-ante prefers being regulated with uncertainty to being regulated with certainty, and its preference ordering is the opposite way if α is above 0.78.*

The parameter α affects the expected welfares of consumers and the monopolist in opposite directions, as expected. Panel (v) of Figure 4 shows that under both certain and uncertain regulations, the expected consumer welfare is always decreasing in α. If α is less than or equal to 0.52, then the optimal probability of regulation is always one, and consumers always prefer the monopolist being regulated with certainty to its being unregulated (the red and blue curves coincide and lie above the green curve). If α is higher than 0.52 but lower than 0.61, then consumers also prefer the monopolist to be regulated with certainty rather than uncertainty (the blue curve lies above the red curve). On the other hand, if $\alpha \geq 0.61$, then consumers attain their highest welfare if the monopolist is regulated with uncertainty (the red curve lies above the other two curves). Moreover, consumers prefer regulation with certainty to no regulation if and only if $\alpha \leq 0.73$.

Result 7. *Consumers ex-ante prefer regulation with uncertainty (regulation with certainty) to no regulation at all percentile values of α (only if $\alpha \leq 0.73$). Moreover, consumers ex-ante prefer regulation with uncertainty to regulation with certainty if and only if $\alpha \geq 0.61$.*

Combining Results 6 and 7, we can see whether any type of regulation may be Pareto superior (more desirable for both consumers and the monopolist) to the other.

Result 8. *There exists no percentile value of α at which regulation with certainty can be Pareto superior to regulation with uncertainty. On the other hand, regulation with uncertainty is Pareto superior to regulation with certainty if α is between 0.61 and 0.78.*

Finally, we illustrate in panel (vi) the effect of α on the expected social welfare. We summarize our observations below.

Result 9. *For any percentile value of α, the expected social welfare is higher under regulation with uncertainty than under no regulation. Regulating the monopolist with uncertainty is also socially more beneficial than regulating it with certainty if $\alpha \geq 0.53$. On the other hand, regulating the monopolist with certainty is socially more beneficial than not regulating it if and only if $\alpha \leq 0.63$.*

3.3 The Effects of c_0 on the SPNE Outcomes

Here, we set $\alpha = 0.5$, $a = 1$, and vary the cost parameter c_0 in the set $\{0.001, \ldots, 0.100\}$ with increments of 0.001 to calculate the effects of c_0 on the equilibrium outcomes. Our computations illustrated in Figure 5 show that the socially-optimal probability of regulation, drawn in panel (i), is between

0 and 1 if c_0 is either sufficiently low (less than a threshold value 0.009) or equal to 0.075, and it is equal to 1 otherwise. Also, this probability is slightly decreasing in c_0 whenever $c_0 < 0.009$. Panel (ii) shows that the R&D investment is decreasing in c_0 while its cost is hump-shaped both in the absence and presence of regulation (with or without certainty). Panels (iv), (v), and (vi) show that the expected welfares of the monopolist, consumers, and the society are decreasing in c_0 over the range of our computations. Moreover, we see that at all values of c_0 the monopolist ex-ante prefers the absence of regulation to the presence of regulation (with or without certainty) whereas the opposite is true about consumers' preferences, as expected. Moreover, for the cost values at which the socially-optimal regulation must be uncertain, the monopolist never wishes that regulation was certain (the red curve is always above the blue curve in panel (iv) when $c_0 \leq 0.009$).

Result 10. *The monopolist ex-ante prefers regulation with uncertainty to regulation with certainty whenever the former is socially optimal, i.e.,* $c_0 \leq 0.009$.

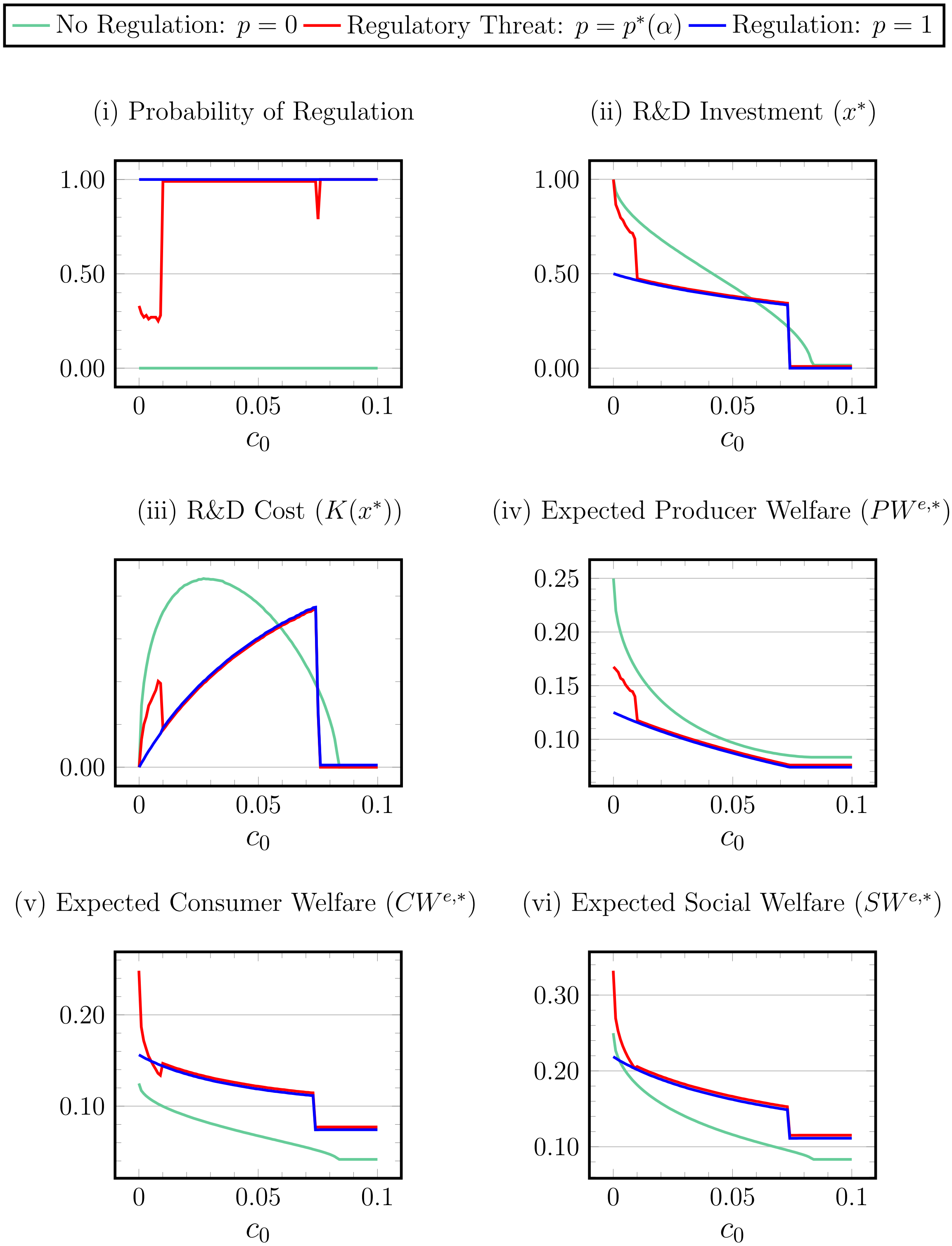
However, the preference of consumers is mixed, as shown in panel (v).

Result 11. *Consumers ex-ante prefer regulation with uncertainty to regulation with certainty if* $c_0 \leq 0.005$ *and the opposite is true if* $0.005 < c_0 \leq 0.009$.

Results 10 and 11 together imply the following.

Result 12. *There exists no value of* c_0 *(in its computational range) at which regulation with certainty can be ex-ante Pareto superior to regulation with uncertainty. On the other hand, regulation with uncertainty is Pareto superior to regulation with certainty if* $c_0 \leq 0.005$.

Figure 5. SPNE Outcomes For Different Values of c_0
($\alpha = 0.5,\ \ a = 1$)



Finally, panel (vi) of Figure 5 shows that the society as a whole ex-ante prefers regulation with uncertainty to the absence of regulation at all values of c_0 in its computational range. It is also true that the society prefers regulation with uncertainty to regulation with certainty if c_0 does not exceed a threshold of 0.009, beyond which the two forms of regulation become equivalent. Interestingly, we also observe that the society ex-ante prefers the absence of regulation to regulation with certainty if $c_0 \leq 0.002$.

4 Conclusion

In this paper, we have attempted to explore whether a natural monopoly with private cost information can reduce the likelihood of regulatory threat by investing in cost-reducing R&D to generate process innovations and whether such an investment can yield Pareto gains in welfare. We have assumed that the regulatory process involves two stages: the ex-ante stage where R&D occurs and the interim stage where regulation occurs possibly with uncertainty. In the ex-ante stage, the regulator and the monopolist play a sequential game. The regulator makes the first strategic move by choosing and announcing the probability that the monopolist will be regulated (according to the mechanism of BM (1982)) in the next (interim) stage where the monopolist will privately learn its marginal cost, and the monopolist, hearing this announcement, chooses the optimal level of its R&D investment. Computing the subgame-perfect Nash equilibrium of this game for a rich set of parameter values, we have showed that leaving the monopolist unregulated cannot be socially optimal under any linear social welfare function (that does not strictly favor the monopolist). The optimal regulatory solution suggests that the monopolist has to be regulated with certainty if the welfare weight of the monopoly, i.e., the parameter α, is below a critical threshold and it has to be regulated with uncertainty otherwise. Moreover, the optimal probability of regulation is found to be nonincreasing in α.

We have also shown that the monopolist's equilibrium R&D is decreasing in the probability of regulation (p); thus it attains its highest level when the monopoly is unregulated ($p = 0$) and its lowest level when the monopoly is regulated with certainty ($p = 1$). When regulation is certain and not necessarily optimal ($p = 1$), the equilibrium R&D is found to be decreasing in the welfare weight, α. However, the results are mixed when regulation is uncertain. If α is less than a critical threshold, then the equilibrium R&D is always decreasing in α and it always realizes at the level which the monopolist would choose when regulation is certain. On the other hand, if α exceeds that threshold, then the equilibrium R&D is always increasing in α and it thus exceeds the level the monopolist would choose when regulation is certain.

Our findings also involve several welfare results. The monopolist ex-ante prefers regulation with certainty to regulation with uncertainty if and only if α is very high. Consumers, on the other hand, prefer regulation with certainty to regulation with uncertainty if and only if α is neither too low nor too high. These results imply that there exists no social welfare function under which regulation with certainty can be Pareto superior (desirable for both consumers and the monopolist) to regulation with uncertainty. On the other hand, regulation with uncertainty can be Pareto superior to regulation with certainty if the welfare weight of the monopolist is sufficiently, but not extremely, high or if the cost of R&D is sufficiently small at any investment level.

One policy recommendation of our results is that a monopolist, with an unknown marginal cost of production and the ability of cost-reducing innovations that are publicly observable, must be optimally regulated with uncertainty rather than certainty so that the monopolist will be induced to choose its R&D at a socially more desirable level provided that the weight of the monopolist's welfare in the social welfare function is sufficiently high and the cost of R&D is sufficiently low.

Future research can fruitfully extend our work in two directions. First, one can study using our setup how the unobservability of R&D expenditures would affect the monopolist's R&D investment under regulatory threat. Second, one can explore how our results would change if the monopolist were assumed to make its R&D investment in the interim stage after it privately learns its marginal cost of production.

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