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Information Acquisition by Price-Setters and Monetary Policy

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Information Acquisition by Price-Setters and Monetary Policy*

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Abstract

In this paper we examine a model where firms decide on the intensity of information acquisition about shocks. We analyze how the monetary policy framework impacts on the aggregate amount of information collected by firms. We show that it is socially beneficial to delegate monetary policy to a conservative central bank even if there are no incentives to push output above its long-run level. Transparency of central banks about economic shocks has ambiguous effects on welfare. If an extreme level of opacity is feasible, it represents the social optimum. Otherwise full transparency may be a second-best solution.

Keywords: conservative central banker, optimal monetary policy, information acquisition, Phillips curve, transparency.

JEL: E58, E13, E12.

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1 Introduction

There is a recent trend to provide microfoundations for macroeconomic relationships such as the Phillips curve. For example, the mechanism introduced by Calvo (1983) derives the Phillips curve by assuming that price-setters have a certain probability of being able to change their prices.[1] An alternative approach has been suggested by Mankiw and Reis (2002). In the spirit of Lucas (1972), they consider information asymmetries in order to motivate a Phillips curve relationship.

Only a few authors endogenize the amount of information acquired by firms. Hamori (1989) analyzes a learning process with endogenous information acquisition by price-setters, who are unsure about the average growth rate of money supply. Sims (2003) examines the effects of limited information processing capabilities. In a recent contribution Reis (2006) proposes a framework where the attentiveness of price-setters is determined endogenously.

In this paper we propose a framework where firms may invest into a costly information collection process in each period. Information collection enables them to learn the value of a markup shock in the subsequent period. We examine how the monetary policy framework impacts on the amount of information collected by firms. In particular, we study the welfare implications of the monetary policy framework along two dimensions: central bank conservatism and transparency.

First, we provide a new argument why an independent and conservative central bank may be desirable even absent an incentive to push output above its natural rate. A famous result by Rogoff (1985) states that in the presence of an inflation bias[2] monetary policy should be delegated to an independent central bank that cares less about output fluctuations compared to society.[3] In our model, appointing a conservative central

[1]For a rigorous treatment cf. Woodford (2003).

[2]The problem of the inflation bias has been analyzed by Kydland and Prescott (1977) and Barro and Gordon (1983).

[3]The importance of the traditional inflation bias/surprise inflation argument has often been doubted, in particular by central bankers (see Blinder (1997)). Herrendorf and Lockwood (1997) show that a stochastic inflation bias arises even when central banks do not target a level of output that is unsustainably high, but when shocks are foreseen by the public.

banker involves two advantages to society. A conservative central banker ensures that price-setters know that prices will not fluctuate widely. This will lead them to pay less attention to shocks. As a consequence, the aggregate costs incurred by all firms for information collection are lower. In addition, if price-setters invest less in information collection, they react less strongly to shocks. This will induce them to choose more stable prices, which is desirable from a social perspective. The optimal policy would not be time-consistent for a central bank sharing the society's preferences, as, once price-setters have chosen to collect less information, such a central bank would have an incentive to stabilize inflation less strongly.

Second, our model enables us to model an increase in central bank transparency as a reduction in the costs that price-setters incur when collecting information.[4] We identify various effects of transparency. In particular, we show that increased transparency leads to a larger fraction of price-setters investing in information acquisition. However, it is unclear whether the aggregate costs of information collection incurred by all firms decrease or not. Moreover, a higher degree of transparency reduces the importance the society attaches to price stability. More transparency unequivocally increases the variance of output. It has ambiguous impacts on the variance of inflation and, ultimately, on welfare.

An extreme degree of opacity, if possible, represents the social optimum. This is a consequence of the facts that transparency makes information acquisition easier for price-setters and that information acquisition involves negative externalities. If it is impossible to achieve a very high level of opacity, full transparency represents a second-best solution.

The paper is organized as follows. In Section 2 we describe our model. We derive the solution in Section 3. The impact of the monetary authority's preferences on the firms' intensity of information collection and on welfare is studied in Section 4. The effects of more transparency of the monetary authority with respect to shocks are analyzed in Section 5. We discuss our findings in Section 6. Section 7 concludes.

[4] The literature on transparency in monetary policy is surveyed by Geraats (2002) and Hahn (2002). A seminal article on transparency has been written by Goodfriend (1986). Other important contributions include Cukierman and Meltzer (1986) and Faust and Svensson (2001).

2 Model

We consider a yeoman farmer model of price-setting under monopolistic competition presented, for example, in Rotemberg and Woodford (1997) and Woodford (2003), chapter 3. The economy is populated by a large number of agents denoted by i. Each agent produces a differentiated good using only his own labor. He sells his good and buys the other agents' goods from the proceeds.

Firms, i.e. consumer-producers, choose the prices p_{ti} for their outputs in each period $t = 1, 2, ...$ The following price-setting equation can be derived from the respective microeconomic optimization problem (the details can be found in Woodford (2003), chapter 3):

$$p_t^* = p_t + \alpha y_t + \varepsilon_t. \tag{1}$$

The optimal price p_t^* depends on the aggregate price level p_t, which reflects strategic complementarities.[5] It also depends on aggregate output y_t, which is common in macroeconomic models (see, e.g., Romer (2005), chapter 6). The optimal price may depend on aggregate output, because aggregate output affects the costs of inputs, such as the real wage, or because of diminishing returns. The positive parameter α determines how strongly output variations affect the firm's optimal price. In addition, we have introduced ε_t which is a normally distributed shock with expected value 0 and variance σ^2. For simplicity, we consider shocks that are not correlated over time and identical for all firms in each period t.

It is important to discuss the nature of the shocks ε_t. We assume that these shocks reflect variations in markups. Formally this could be described by a stochastic sales tax on all goods, where revenues are used to finance lump-sum transfers to the agents.[6] Markup shocks can also be motivated by changes in the intensity of competition or in the aggressiveness of wage bargainers. It is important to stress that these shocks

[5]Note that we neglect the firm index for the optimal price p_t^*, because this price is identical for all firms.

[6]For a discussion of markup shocks see, e.g., Ball et al. (2005). See also the discussion in Woodford (2002), pp. 44-45. Clarida et al. (1999), among others, use the term "cost-push" shock for socially inefficient disturbances.

impact on the equilibrium level of output without information asymmetries, but do not affect the socially efficient level of output. As a consequence, monetary policy should aim at stabilizing these shocks to some extent. Markup shocks are considered by many authors; among them are Clarida et al. (2002), Steinsson (2003), Woodford (2003), and Ball et al. (2005). We take up this point again in Section 6.

We assume that prices are fully flexible. However, some firms may act on the basis of outdated information. The reason may be that information processing is costly and the benefits from always being well-informed may not be very large. In each period, firms can decide to invest a fixed amount of resources $c > 0$ in order to obtain precise information about the markup shock in the next period. Thus we assume that it takes some time before the benefits from investments in information collection accrue.

If a firm does not invest in information collection, it must base its decision on outdated information. We make the assumption that these firms can always use the information that was available in the previous period. This is not implausible because the size of the shock in the previous period can be derived from the size of the past price level and output, both of which are rather easy to observe. By contrast, the price level and output in the current period cannot be observed directly, since the firm has to choose its price simultaneously with the other price-setters. We introduce λ to denote the fraction of firms investing in information collection. Consequently, λc describes the aggregate costs of information collection incurred by all firms.

A second-order Taylor approximation of the firm's profit function yields that profits are quadratically decreasing in the difference between the price set by the firm and the optimal price.[7] Therefore the costs from choosing a price $\mathbb{E}_{t-1} p_t^*$ based on outdated information rather than the optimal price p_t^* are given by

$$\mathbb{E}_{t-1}\left(p_t^* - \mathbb{E}_{t-1} p_t^*\right)^2 - \mathbb{E}_{t-1}\left(p_t^* - p_t^*\right)^2 = \mathbb{E}_{t-1}\left(p_t^* - \mathbb{E}_{t-1} p_t^*\right)^2 . \tag{2}$$

The social loss function is given by

$$L_{SOC} = \frac{1-\lambda}{\lambda} a_{SOC} \pi_t^2 + y_t^2 + b_{SOC} \lambda c, \tag{3}$$

[7] For the details of the derivation see Woodford (2003).

where a_{SOC} and b_{SOC} are weakly positive parameters and $\pi_t := p_t - p_{t-1}$ denotes the inflation rate.

Proposition 1

This form of loss function can be derived from microeconomic foundations.

The proofs of this and subsequent propositions are contained in the Appendix.

For a fixed level of λ, Equation (3) encompasses the standard loss function that depends only on deviations of inflation from its target and from deviations of output from the natural level. The term $\frac{1-\lambda}{\lambda} a_{SOC}\pi_t^2$ captures the distortions arising from price dispersion in period t. For $\lambda \to 1$, this term vanishes, as $\lambda \to 1$ implies that all firms are perfectly informed and thus adopt the same price.[8] The term y_t^2 reflects the costs stemming from deviations of output from its socially optimal level. Finally, the aggregate costs of information collection, which are given by λc, have to be taken into account. Parameter b_{SOC} gives the importance society attaches to these costs. In principle, parameters a_{SOC} and b_{SOC} could be derived from the structural parameters of the underlying yeoman farmer model.

We have not specified yet how monetary policy is conducted. The central bank chooses y_t to minimize the central bank loss function[9]

$$L_{CB} = a_{CB}\pi_t^2 + y_t^2 + b_{CB}\lambda c, \tag{4}$$

where a_{CB} and b_{CB} are weakly positive parameters. Parameter a_{CB} describes the degree of the central bank's conservatism. If a_{CB} is very low, then the central bank cares very much about output stabilization compared to inflation stabilization. This form of loss function implies that the central bank targets an inflation rate of 0 and the natural rate of output. Thus the standard time-inconsistency problem plays no role in our model. We have included the term $b_{CB}\lambda c$ to make the central bank's loss function formally equivalent to the social loss function. If we set $b_{CB} = 0$, we obtain

[8] The term is also zero for $\lambda = 0$ because this can be shown to imply $\pi_t = 0$.

[9] Of course, central banks cannot affect output directly. We have in mind that the central bank chooses an interest rate which affects output via an IS-relationship. Modeling this relationship explicitly would not affect our results.

the more standard central bank loss function $L_{CB} = a_{CB}\pi_t^2 + y_t^2$. For $a_{CB} = \frac{1-\lambda}{\lambda}a_{SOC}$ and $b_{CB} = b_{SOC}$, the preferences of the central bank reflect those of society.

The sequence of events in every period t is as follows:

1. The central bank learns the value of the shock ε_t.
2. The firms that have invested c in the previous period obtain accurate information about the realization of the shock. The other firms must base their decision on the information set available in period $t-1$.
3. Simultaneously, firms choose the prices for their outputs and the central bank chooses output (by varying the interest rate, which is not modeled explicitly).
4. The firms decide whether or not to invest c in order to obtain new information in period $t+1$.

3 Solution

In Appendix A we show that, with the inflation rate $\pi_t := p_t - p_{t-1}$, a Neoclassical Phillips curve can be formulated as

$$\pi_t = \mathbb{E}_{t-1}\pi_t + \kappa\alpha y_t + \kappa\varepsilon_t, \tag{5}$$

where we have introduced the variable κ as follows

$$\kappa := \frac{\lambda}{1-\lambda}. \tag{6}$$

Note that λ (and thus κ) will be determined endogenously in our model from the firms' decisions whether or not to acquire information. Variable κ is a monotonically increasing function of λ.

Since the firms have made their decisions concerning information collection in the last period, the central bank takes λ and thus κ as given when deciding on which size of output to choose. Inserting the Phillips curve into the central bank's loss function (4), we obtain:

$$L_{CB} = a_{CB}\left(\mathbb{E}_{t-1}\pi_t + \kappa\alpha y_t + \kappa\varepsilon_t\right)^2 + y_t^2 + b_{CB}\lambda c \tag{7}$$

Then the first-order condition for optimal policy is

$$2a_{CB}\alpha\kappa\left(\mathbb{E}_{t-1}\pi_t + \kappa\alpha y_t + \kappa\varepsilon_t\right) + 2y_t = 0. \tag{8}$$

Taking expectations and re-arranging yields

$$a_{CB}\alpha\kappa\mathbb{E}_{t-1}\pi_t + (1 + a_{CB}\alpha^2\kappa^2)\mathbb{E}_{t-1}y_t = 0. \tag{9}$$

Taking expectations of (5) and applying $\mathbb{E}_{t-1}\varepsilon_t$, we can assert that $\mathbb{E}_{t-1}y_t = 0$. Together with Equation (9) we obtain that inflation expectations must also be zero

$$\mathbb{E}_{t-1}\pi_t = 0. \tag{10}$$

If we insert this into the first-order condition (8), we obtain the equilibrium output.

$$y_t = -\frac{a_{CB}\alpha\kappa^2}{1 + a_{CB}\alpha^2\kappa^2}\varepsilon_t \tag{11}$$

If a positive shock occurs, the central bank lowers output somewhat to fight inflation. The reverse happens for a negative shock. The variance of equilibrium output is a monotonically increasing function of κ and thus of λ. This means that the impact of distortionary markup shocks on output is the stronger, the more agents observe the shocks. For $\kappa = 0$ (or $\lambda = 0$), all agents are ignorant of the shock and output always corresponds to its socially optimal level $y_t = 0$.

Using (5), (10) and (11), the equilibrium value of the inflation rate can be written as

$$\pi_t = \frac{\kappa}{1 + a_{CB}\alpha^2\kappa^2}\varepsilon_t. \tag{12}$$

The impact of shocks on inflation is partially stabilized by the central bank, the less so the lower the value of a_{CB}. While the variance of output is a monotonically increasing function of κ, the same is not true for the variance of inflation. It increases for small values of κ and λ, and it decreases for large values of these variables.

Substituting (11) and (12) into (4) yields the following expression for the central bank's expected losses

$$\begin{aligned} L_{CB} &= \frac{\kappa^2}{1 + a_{CB}\alpha^2\kappa^2}\sigma^2 + b_{CB}\lambda c \\ &= \frac{\lambda^2}{(1-\lambda)^2 + a_{CB}\alpha^2\lambda^2}\sigma^2 + b_{CB}\lambda c. \end{aligned} \tag{13}$$

If we insert (11) and (12) into (3), we see that expected social losses in equilibrium are given by

$$\begin{aligned} L_{SOC} &= \frac{1-\lambda}{\lambda} a_{SOC} \frac{\kappa^2}{(1+a_{CB}\alpha^2\kappa^2)^2}\sigma^2 + \frac{a_{CB}^2\alpha^2\kappa^4}{(1+a_{CB}\alpha^2\kappa^2)^2}\sigma^2 + b_{SOC}\lambda c \\ &= \frac{a_{SOC}\lambda(1-\lambda)^3}{((1-\lambda)^2+a_{CB}\alpha^2\lambda^2)^2}\sigma^2 + \frac{a_{CB}^2\alpha^2\lambda^4}{((1-\lambda)^2+a_{CB}\alpha^2\lambda^2)^2}\sigma^2 + b_{SOC}\lambda c. \end{aligned} \tag{14}$$

L_{SOC} is zero for $\lambda = 0$. This finding can be interpreted in the following way. Recall that we consider markup shocks, which represent socially detrimental fluctuations. This has the consequence that the social optimum can be achieved only if all price-setters ignore these shocks. This corresponds to $\lambda = 0$.

Note that parameter b_{CB} does not affect the central bank's behavior. Therefore social losses are invariant to changes in b_{CB}. Without loss of generality we can set $b_{CB} = 0$ for the remainder of our paper. Now let us consider for the moment that λ is fixed.

Proposition 2

If λ is exogenous, it is optimal to delegate monetary policy to a central bank that shares the same emphasis on price stability, i.e. $a_{CB} = \frac{1-\lambda}{\lambda}a_{SOC}$.

Proposition 2 has the crucial implication that there is no rationale for the delegation of monetary policy to a conservative central banker if λ is fixed. We will show that this finding is no longer valid, once we endogenize the amount of information collected by firms.

The amount of information collected by firms is given in the next proposition.

Proposition 3

A unique equilibrium level of λ exists. It is given by

$$\lambda(a_{CB}, c) = \begin{cases} 0 & \text{for } \lambda_1 \notin \mathbb{R} \\ \lambda_1 & \text{for } \lambda_1 \leq 1 \\ 1 & \text{for } \lambda_1 > 1, \end{cases} \tag{15}$$

where

$$\lambda_1 = \frac{1 + \sqrt{\frac{\sigma}{\sqrt{c}} + a_{CB}\alpha^2\left(\frac{\sigma}{\sqrt{c}} - 1\right)}}{1 + a_{CB}\alpha^2}. \tag{16}$$

The equilibrium level of λ can be interpreted in two ways. If we consider an equilibrium in pure strategies, then a fraction λ of firms collect information with certainty, while the rest of the firms do not collect information. However, it may seem unclear how firms can coordinate on such an equilibrium. Therefore our preferred interpretation is that all firms have probability λ of collecting information and probability $1 - \lambda$ of not collecting information. This corresponds to a symmetric equilibrium in mixed strategies.[10]

It is interesting to note that the equilibrium level of λ depends on a_{CB}, which is the significance the central bank attaches to price stability. This effect is studied in more detail in the following section.

4 Optimal Degree of Central Bank Conservatism

In this section we show that social losses can be lowered by delegating monetary policy to a central bank that attaches less importance to output fluctuations than society. There are at least two ways in which the government can affect parameter a_{CB} of the central bank's loss function. First, the government can appoint central bankers with preferences that differ from social preferences (cf. Rogoff (1985)). Second, the government could use incentive contracts to motivate central banks to behave in a certain way (cf. Walsh (1995)). Recall that b_{CB} does not have an impact on the central bank's behavior and thus does not affect social losses.

In the following proposition, we examine the impact of an increase in a_{CB} on the equilibrium value of λ.

Proposition 4

The function $\lambda(a_{CB}, c)$ is weakly decreasing in a_{CB}.

The intuition is straightforward. If the central bank puts more emphasis on price stability, then information collection becomes less attractive to firms, because the costs of choosing a price based on outdated information depend positively on the variance of

[10]The law of large numbers implies that the fraction of price-setters investing in information acquisition amounts to λ for this equilibrium.

the price level. As a consequence the fraction of firms collecting information decreases if a_{CB} increases.

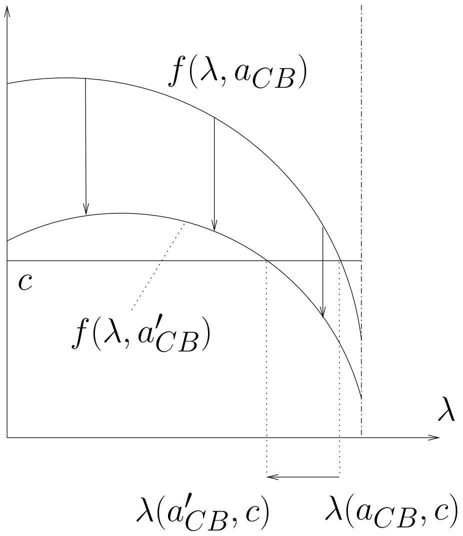

Figure 1: The impact of an increase in a_{CB} on the equilibrium value of λ.

The proof can also be illustrated by means of Figure 1. In the proof of Proposition 4, we define $f(\lambda, a_{CB})$ as the benefits from being informed. For an interior solution firms must be indifferent with respect to collecting information or not. This means that an interior solution is determined by the intersection of the graph of $f(\lambda, a_{CB})$ and the graph of the constant function c. An increase from a_{CB} to a'_{CB} decreases the benefits from being informed and thus shifts the curve $f(\lambda, a_{CB})$ downwards. This implies that the equilibrium value of λ decreases.[11]

It is instructive to consider the polar cases $a_{CB} = 0$ and $a_{CB} \to \infty$. In the first case the central bank attaches no significance to price stability. In the second case the central bank regards the objective of price stability as paramount.

Proposition 5

If the central bank cares very much about price stability, then no price-setter collects information:

$$\lim_{a_{CB} \to \infty} \lambda(a_{CB}, c) = 0. \tag{17}$$

[11] Analogously, one can also show that the equilibrium level $\lambda(a_{CB}, c)$ is weakly increasing in the variance of the shocks σ. The intuition for this result is clear. Larger shocks make decisions based on outdated information more costly and thus induce more price-setters to acquire information, which is reflected by a larger value of λ.

If the central bank does not care about price stability, then all price-setters collect information:

$$\lambda(0, c) = 1. \tag{18}$$

It is a striking feature of our model that the emphasis the society puts on price stability, which is given by $\frac{1-\lambda(a_{CB},c)}{\lambda(a_{CB},c)} a_{SOC}$ (see (3)), depends on the degree of conservatism a_{CB} of the central bank. According to Proposition 4, $\frac{1-\lambda(a_{CB},c)}{\lambda(a_{CB},c)} a_{SOC}$ is an increasing function of a_{CB}. From this we conclude that the society values the objective of price stability the more, the higher the weight the central bank attaches to price stability is.

This can be given the following interpretation. For simplicity, assume that the inflation rate is given by 1 and that (the log of) the price level in the previous period was zero. Price-setters who have not collected information always choose a price that equals the price level in the previous period, which is zero in our example. An inflation rate of 1 necessarily means that the fraction λ of price setters who have acquired new information choose a price $\frac{1}{\lambda}$. If λ is very small, $\frac{1}{\lambda}$ is very large. As a consequence, there is a considerable difference between the price chosen by price setters who have obtained new information and the price chosen by price-setters with outdated information. For small λ, the distortions stemming from price dispersion are thus substantial. Hence, a specified inflation rate involves higher social costs if λ is low rather than high.

It is instructive to consider welfare for two polar cases.

Proposition 6

For $a_{CB} \to 0$ and $a_{CB} \to \infty$ we obtain

$$\lim_{a_{CB}\to 0} L_{SOC} = \frac{1}{\alpha^2}\sigma^2 + b_{SOC}c, \tag{19}$$

$$\lim_{a_{CB}\to \infty} L_{SOC} = \begin{cases} 0 & \text{for } \sigma < \sqrt{c} \\ \frac{1}{\alpha^2}\left(\sigma - \sqrt{c}\right)^2 & \text{for } \sigma \geq \sqrt{c}. \end{cases} \tag{20}$$

Proposition 6 implies that an extremely conservative central bank ($a_{CB} \to \infty$) is always more desirable from a social perspective than a central bank that puts a very low emphasis on price stability ($a_{CB} \to 0$). In fact, one can even show that

Proposition 7

It is socially optimal to delegate monetary policy to a central bank that places a very high emphasis on inflation ($a_{CB} \to \infty$).

A sufficiently high degree of central bank conservatism prevents price-setters from collecting information. This is beneficial to society because of the negative externalities stemming from information collection. This point is discussed in more detail in Section 6.

5 Transparency

Our model also enables us to examine the issue of transparency in monetary policy. It seems natural to assume that an increased level of central bank transparency about economic shocks results in lower costs of information acquisition for price-setters, i.e. in a lower value of c. The implication of lower costs for the fraction of firms collecting information in equilibrium is studied in the following proposition:

Proposition 8

An increase in transparency modeled as a marginal decrease in costs c leads to a weak increase in $\lambda(a_{CB}, c)$.

The finding of the proposition is intuitively clear: It states that more firms gather information if this is less costly.

With this proposition, we can analyze additional effects of transparency. First, Equation (11) implies that an increase in transparency increases the variance of output. This is plausible because transparency makes price-setters better informed on average, which makes them more responsive to shocks. Second, transparency may or may not lower the variance of inflation (compare Equation (12)). Third, transparency lowers the importance society assigns to price stability. This follows from the observation that $\frac{1-\lambda(a_{CB},c)}{\lambda(a_{CB},c)} a_{SOC}$ is a decreasing function of c. Fourth, we obtain the paradoxical result that the aggregate costs of information collection, which are given by $\lambda(a_{CB}, c)c$, may increase if the costs of collecting information decrease for individual firms. This occurs if the elasticity of $\lambda(a_{CB}, c)$ with respect to c, which amounts to $\frac{\partial\lambda(a_{CB},c)}{\partial c} \cdot \frac{c}{\lambda(a_{CB},c)}$, is smaller than -1. It is readily verified that total costs $\lambda(a_{CB}, c)c$ as a function of c are hump-shaped. Fifth, the welfare implications of a marginal increase in transparency cannot be pinned down. For example, if b_{CB} is sufficiently large, then social losses are dominated by the costs of searching for information, which, as mentioned before, are hump-shaped.

It is again instructive to calculate $\lambda(a_{CB}, c)$ for two polar cases.

Proposition 9

The fraction of firms acquiring information satisfies:

$$\lambda(a_{CB}, c) = 1 \qquad \text{for } c \leq \frac{\sigma^2}{a_{CB}^2\alpha^4}, \tag{21}$$

$$\lambda(a_{CB}, c) = 0 \qquad \text{for } c > (1 + a_{CB}\alpha^2)^2\frac{\sigma^2}{a_{CB}^2\alpha^4}. \tag{22}$$

The case $c > (1 + a_{CB}\alpha^2)^2\frac{\sigma^2}{a_{CB}^2\alpha^4}$ represents an extreme degree of intransparency. The central bank implements high costs c, which ensures that the benefits from collecting information $f(a_{CB}, \lambda)$ are lower than c for all λ. As a result, no price-setter collects information.

The next proposition gives social losses for very low costs of information collection and for very high costs.

Proposition 10

Social losses are given by

$$L_{SOC} = \frac{1}{\alpha^2}\sigma^2 + b_{SOC}c \qquad \text{for } c \leq \frac{\sigma^2}{a_{CB}^2\alpha^4}, \tag{23}$$

$$L_{SOC} = 0 \qquad \text{for } c > (1 + a_{CB}\alpha^2)^2\frac{\sigma^2}{a_{CB}^2\alpha^4}. \tag{24}$$

Consequently, an extreme level of opacity, if attainable, is socially desirable. We summarize this important finding in the following proposition

Proposition 11

A sufficiently high level of intransparency, i.e. sufficiently high costs of information acquisition $c > \frac{(1+a_{CB}\alpha^2)^2}{a_{CB}^2\alpha^4}\sigma^2$*, represents the social optimum.*

If the costs of information acquisition are very high, then firms abstain from collecting information. This is socially desirable because it prevents markup shocks from distorting output.

However, one has to keep in mind that price-setters may obtain information from other sources than the central bank. For example, firms may observe shocks directly. The costs associated with observing shocks through other sources therefore represent an upper bound when the central bank chooses c. While the central bank may be able to reduce the costs associated with information collection to a large extent by publishing information, it cannot increase the costs of information collection arbitrarily.

We note that social losses as a function of c are hump-shaped. Formally this result is supported by the following facts. Social losses attain their minimum value for high costs, and the derivative of social losses with respect to c is positive for small c.[12] Thus full transparency, i.e. $c = 0$, may represent a second-best solution if an extreme level of opacity is not attainable. Full transparency involves two advantages. First, it eliminates the costs incurred by price-setters for information collection. Second, full transparency implies that all firms are equally well informed and therefore choose identical prices. This disposes of distortions stemming from price dispersion. The drawback of full transparency is a considerable deviation of output from the socially optimal level.

Our results on transparency are somewhat related to Gersbach (1998), who shows that complete transparency about economic disturbances is inferior to complete opacity. For the polar cases $c = 0$ and $c \to \infty$ we obtain identical conclusions with regard to welfare, although the underlying mechanism is quite different. Our paper enables us to examine also intermediate degrees of transparency, which seems particularly important if complete opacity is impossible. Moreover, in our framework with microfoundations we identify several new effects. For example, the degree of central bank transparency affects the structural parameters of the Phillips curve. It also impacts on the em-

[12] This can be checked by means of Proposition 10.

phasis society attaches to price stability and on the aggregate costs of searching for information.

The new effects identified in this paper highlight that modeling the information collection process explicitly is also fruitful for analyses of transparency in monetary policy. To my knowledge, an explicit analysis of firms' costs and benefits from information acquisition has not been undertaken in the literature on transparency in monetary policy so far.

6 Discussion

In our paper we consider markup shocks. These shocks do not impact on the socially optimal level of output. However, they affect the output level that would prevail without surprises in the price level. All producer-consumers in the underlying yeoman farmer model would be better off if they could commit to ignoring the shocks. However, such a commitment is not feasible, because it is individually rational to respond to the shocks if they are known.

Hence information collection may be beneficial to individual producer-consumers, but it involves negative externalities to other agents. As a result, the level of information collected in equilibrium may be inefficiently high. High degrees of conservatism or opacity reduce the amount of information collected by agents and are thus beneficial.

Woodford (2002), pp. 44-45, argues that other types of shocks, like technology shocks, preference shocks and variations in government spending, cause the socially optimal level of output and the output level without price surprises to move in lockstep. In other words, these shocks do not affect the degree of inefficiency. He proves that complete price stability is optimal in these cases. In our paper, we show that, even if we consider markup shocks, which create variations in the degree of inefficiency, a high preference for price stability on the part of the central bank may be optimal if we consider endogenous information acquisition by price-setters.

7 Conclusions

In this paper we have proposed a model where price-setters can decide whether to acquire information about economic disturbances or not. We have analyzed the repercussions of the monetary policy framework along two dimensions.

First, we have studied the consequences of monetary policy delegation. We have shown that the delegation of monetary policy to a conservative central bank reduces the amount of resources spent on information collection. This is desirable from a perspective of welfare, because it minimizes the socially detrimental effects of markup shocks. It is important to note that this argument for the delegation of monetary policy to a conservative central banker does not hinge on an incentive to push output growth above its long-run natural rate.

Second, we have analyzed transparency in monetary policy. A marginal increase in transparency always leads to a larger fraction of well-informed firms. Interestingly, a decrease in the costs an individual firm has to incur in order to acquire information may result in an increase in the aggregate amount of resources spent on information collection by all firms. The overall impact of a marginal increase in transparency on welfare cannot be pinned down. If extreme opacity is possible, then this represents the social optimum. If a sufficiently high level of opacity cannot be attained, full transparency is a second-best solution.

A Derivation of the Phillips Curve

Recall that, in each period t, a fraction λ of the price-setters become informed and set their optimal price $p_{ti} = p_t^*$. The rest of the price-setters can only use outdated information. Thus, these price-setters choose $p_{ti} = \mathbb{E}_{t-1}p_t^*$. Then the aggregate price level can be written in the following way

$$p_t = \lambda p_t^* + (1-\lambda)\mathbb{E}_{t-1}p_t^*. \tag{25}$$

Using (1), this can be rearranged as

$$p_t \quad = \quad \lambda(p_t + \alpha y_t + \varepsilon_t) + (1-\lambda)\mathbb{E}_{t-1}(p_t + \alpha y_t + \varepsilon_t).$$

Taking expectations at time $t-1$ yields

$$\alpha\mathbb{E}_{t-1}y_t + \mathbb{E}_{t-1}\varepsilon_t = 0 \tag{26}$$

Since the expected value of the shock is zero ($\mathbb{E}_{t-1}\varepsilon_t = 0$), equation (26) implies that $\mathbb{E}_{t-1}y_t = 0$ holds. Therefore the price level is given by

$$p_t = \lambda(p_t + \alpha y_t + \varepsilon_t) + (1-\lambda)\mathbb{E}_{t-1}p_t, \tag{27}$$

which can be rewritten as

$$(1-\lambda)\left(p_t - \mathbb{E}_{t-1}p_t\right) = \lambda(\alpha y_t + \varepsilon_t). \tag{28}$$

Together with $\pi_t := p_t - p_{t-1}$ and $\kappa := \frac{\lambda}{1-\lambda}$ we obtain (5).

□

B Proof of Proposition 1

Let us neglect the costs of gathering information for the moment. Thus, we consider Equation (3) for $b_{SOC} = 0$. Woodford (2002) shows that in this case optimal monetary policy involves a minimization of a weighted average of the variance of prices and the variance of output. Using the fact that a fraction λ of the firms chooses prices $p_{ti} = p_t^*$

and a fraction $1-\lambda$ chooses $p_{ti} = \mathbb{E}_{t-1}p_t^*$, the variance of prices in our model can be written as

$$\begin{aligned}
\mathrm{Var}_i\, p_{ti} &= \lambda \left(p_t^* - p_t\right)^2 + (1-\lambda)\left(\mathbb{E}_{t-1}p_t^* - p_t\right)^2 \\
&= \lambda \left[p_t^* - (\lambda p_t^* + (1-\lambda)\mathbb{E}_{t-1}p_t^*)\right]^2 + (1-\lambda)\left[\mathbb{E}_{t-1}p_t^* - (\lambda p_t^* + (1-\lambda)\mathbb{E}_{t-1}p_t^*)\right]^2 \\
&= \lambda(1-\lambda)^2 \left(\mathbb{E}_{t-1}p_t^* - p_t^*\right)^2 + (1-\lambda)\lambda^2 \left(\mathbb{E}_{t-1}p_t^* - p_t^*\right)^2 \\
&= \lambda(1-\lambda)\left(\mathbb{E}_{t-1}p_t^* - p_t^*\right)^2,
\end{aligned}$$

where we have used (25). Applying (1), (28), and $\mathbb{E}_{t-1}\varepsilon_t = 0$ yields

$$\begin{aligned}
& p_t^* - \mathbb{E}_{t-1}p_t^* \\
=\ & p_t + \alpha y_t + \varepsilon_t - \mathbb{E}_{t-1}p_t - \alpha \mathbb{E}_{t-1}y_t - \mathbb{E}_{t-1}\varepsilon_t \\
=\ & p_t + \frac{1-\lambda}{\lambda}(p_t - \mathbb{E}_{t-1}p_t) - \mathbb{E}_{t-1}p_t \\
=\ & \frac{1}{\lambda}(p_t - \mathbb{E}_{t-1}p_t).
\end{aligned}$$

We obtain

$$\begin{aligned}
\mathrm{Var}_i\, p_{ti} &= \lambda(1-\lambda)\left(\mathbb{E}_{t-1}p_t^* - p_t^*\right)^2 \\
&= \frac{1-\lambda}{\lambda}(p_t - \mathbb{E}_{t-1}p_t)^2 \\
&= \frac{1-\lambda}{\lambda}(\pi_t - \mathbb{E}_{t-1}\pi_t)^2.
\end{aligned} \tag{29}$$

This expression can also be found in Woodford (2002), p. 19, for a model with predetermined prices.

Equation (29) implies that social losses depend on the difference of the price level from the expected price level, because $(p_t - \mathbb{E}_{t-1}p_t)^2$ enters the social loss function. As a consequence, infinitely many paths of the price level are equivalent with respect to welfare. This allows us to single out one of the expected paths of the price level. Introducing some (possibly very small) costs of inflation that are not captured by our model, we assume that the central bank chooses one particular path, namely a path where expected inflation is zero. This gives

$$\mathrm{Var}_i\, p_{ti} = \frac{1-\lambda}{\lambda}\pi_t^2. \tag{30}$$

Thus, without costs of gathering information, the social loss function can be written as (3) with $b_{CB} = 0$. However, in our model we also have to consider the impact of the costs stemming from information collection on welfare. The aggregate costs of information collection are λc. Hence we arrive at the social loss function in Equation (3), where parameter b_{SOC} measures the significance of the costs mentioned above. In principle, parameters a_{SOC} and b_{SOC} could be derived from the structural parameters of the underlying yeoman farmer model.

□

C Proof of Proposition 2

We show that social losses attain their minimum value for $a_{CB} = \frac{1-\lambda}{\lambda} a_{SOC}$. The derivative of (14) with respect to a_{CB} amounts to

$$\begin{aligned}\frac{\partial L_{SOC}}{\partial a_{CB}} &= \frac{2a_{CB}\alpha^2\lambda^4\left((1-\lambda)^2 + a_{CB}\alpha^2\lambda^2\right) - 2\alpha^2\lambda^2\left(a_{SOC}\lambda(1-\lambda)^3 + a_{CB}^2\alpha^2\lambda^4\right)}{((1-\lambda)^2 + a_{CB}\alpha^2\lambda^2)^3}\sigma^2 \\ &= 2\alpha^2\lambda^3(1-\lambda)^2\frac{a_{CB}\lambda - a_{SOC}(1-\lambda)}{((1-\lambda)^2 + a_{CB}\alpha^2\lambda^2)^3}\sigma^2.\end{aligned}$$

The derivative is zero for $a_{CB} = \frac{1-\lambda}{\lambda} a_{SOC}$. It is also straightforward to show that the second derivative is positive.

□

D Proof of Proposition 3

In the following, we show how λ is determined. For this purpose we rewrite (2) as follows

$$\begin{aligned}(p_t^* - \mathbb{E}_{t-1}p_t^*)^2 &= \left[\pi_t - \mathbb{E}_{t-1}\pi_t + \alpha(y_t - \mathbb{E}_{t-1}y_t) + \varepsilon_t - \mathbb{E}_{t-1}\varepsilon_t\right]^2 \\ &= \left(\pi_t + \alpha y_t + \varepsilon_t\right)^2 \\ &= \frac{(1+\kappa)^2}{(1 + a_{CB}\alpha^2\kappa^2)^2}\varepsilon_t^2,\end{aligned}$$

where we have applied the fact that $\mathbb{E}_{t-1}y_t = 0$. Now the expected costs from using outdated information are given by

$$\mathbb{E}_{t-1}(p_t^* - \mathbb{E}_{t-1}p_t^*)^2 = \frac{(1+\kappa)^2}{(1+a_{CB}\alpha^2\kappa^2)^2}\sigma^2. \tag{31}$$

or, as a function of λ instead of κ,

$$f(\lambda, a_{CB}) := \frac{1}{[(1-\lambda)^2 + a_{CB}\alpha^2\lambda^2]^2}\sigma^2. \tag{32}$$

Function $f(\lambda, a_{CB})$ represents the expected benefits of obtaining an accurate signal about the economic disturbance ε_t. It is straightforward to derive that $f(\lambda, a_{CB})$ has a maximum at $\lambda_{MAX} = \frac{1}{1+a_{CB}\alpha^2}$ with $f(\lambda_{MAX}, a_{CB}) = \frac{(1+a_{CB}\alpha^2)^2}{(a_{CB}\alpha^2)}$. We observe that $0 < \lambda_{MAX} < 1$. $f(\lambda, a_{CB})$ is strictly increasing for $\lambda < \lambda_{MAX}$ and strictly decreasing for $\lambda > \lambda_{MAX}$.

All firms are indifferent with respect to investing in information acquisition or not if[13]

$$f(\lambda, a_{CB}) = c. \tag{33}$$

This is equivalent to[14]

$$(1-\lambda)^2 + a_{CB}\alpha^2\lambda^2 = \frac{\sigma}{\sqrt{c}}. \tag{34}$$

This quadratic equation has two solutions:

$$\lambda_1 = \frac{1+R}{1+a_{CB}\alpha^2}, \tag{35}$$

$$\lambda_2 = \frac{1-R}{1+a_{CB}\alpha^2}, \tag{36}$$

where we have introduced

$$R := \sqrt{\frac{\sigma}{\sqrt{c}} + a_{CB}\alpha^2\left(\frac{\sigma}{\sqrt{c}} - 1\right)}. \tag{37}$$

At $\lambda = \lambda_2$, $f(\lambda, a_{CB})$ intersects the graph of the constant function c from below, which follows from the facts that $f(\lambda, a_{CB})$ is strictly increasing for $\lambda \leq \lambda_{MAX}$ and that $\lambda_2 < \lambda_{MAX}$. This implies that the respective equilibrium would be unstable, because a

[13]We could also consider the identity $\delta f(\lambda, a_{CB}) = c$ with a discount factor δ here. Setting $\delta = 1$ simplifies the exposition and does not affect our findings.

[14]We neglect the negative root here, which would yield a complex solution for λ.

marginal increase in the fraction of firms investing in information collection would make information collection more attractive to all firms. By contrast, analogous arguments show that λ_1 represents a stable equilibrium. The equilibrium value of λ as a function of a_{CB} is therefore given by

$$\lambda(a_{CB}, c) = \begin{cases} 0 & \text{for } \lambda_1 \notin \mathbb{R} \\ \lambda_1 & \text{for } \lambda_1 \in [0; 1] \\ 1 & \text{for } \lambda_1 > 1. \end{cases} \tag{38}$$

This can be explained as follows. If λ_1 is not a real number, the costs c of information collection are larger than $f(\lambda, a_{CB})$ $\forall \lambda \in [0; 1]$. In this case it is optimal for all firms to refrain from investing in information collection. If $\lambda_1 > 1$, we obtain a corner solution where all firms strictly prefer to collect information.

□

E Proof of Proposition 4

In this proof we show that $\lambda(a_{CB}, c)$ is a weakly decreasing function of a_{CB}. Let us assume for the moment that $\sigma < \sqrt{c}$. Then we can distinguish between three cases.

First, for $0 \leq a_{CB} \leq \frac{\sigma}{\alpha^2}\frac{1}{\sqrt{c}}$, $\lambda_1 \geq 1$ (see (16)). Equation (15) then yields $\lambda(a_{CB}, c) = 1$.

Second, for $\frac{\sigma}{\alpha^2}\frac{1}{\sqrt{c}} < a_{CB} \leq \frac{\sigma}{\alpha^2}\frac{1}{\sqrt{c}-\sigma}$, we obtain $\lambda_1 < 1$. Consequently, $\lambda(a_{CB}, c) = \lambda_1$. Therefore we have to compute the derivative of λ_1 with respect to a_{CB}. According to Equations (35) and (37), this derivative can be calculated as

$$\begin{aligned} \frac{\partial \lambda_1}{\partial a_{CB}} &= \frac{(1 + a_{CB}\alpha^2)\frac{1}{2}\alpha^2\left(\frac{\sigma}{\sqrt{c}} - 1\right)R^{-1} - \alpha^2(1+R)}{(1 + a_{CB}\alpha^2)^2} \\ &= \alpha^2 \frac{\frac{1}{2}(R^2 - 1) - R(1+R)}{R(1 + a_{CB}\alpha^2)^2} \\ &= -\frac{1}{2}\alpha^2 \frac{(R+1)^2}{R(1 + a_{CB}\alpha^2)^2}. \end{aligned}$$

This expression is strictly negative, which implies $\frac{\partial \lambda}{\partial a_{CB}}(a_{CB}, c) < 0$ for intermediate values of a_{CB}.

Third, for $a_{CB} > \frac{\sigma}{\alpha^2}\frac{1}{\sqrt{c}-\sigma}$, λ_1 is not a real number. Proposition 3 states that $\lambda(a_{CB}, c) = 0$ in this case.

To sum up, $\lambda(a_{CB}, c)$ is a weakly decreasing function of a_{CB} under the assumption that $\sigma < \sqrt{c}$. For $\sigma \geq \sqrt{c}$, the proof is almost identical.

□

F Proof of Proposition 5

First, we consider $a_{CB} \to \infty$. If $\frac{\sigma}{\sqrt{c}} < 1$, then λ_1 as defined in (16) is not a real number for sufficiently large a_{CB}. As a consequence Proposition 3 yields $\lambda(a_{CB}, c) = 0$. If $\frac{\sigma}{\sqrt{c}} \geq 1$, λ_1 converges to zero for $a_{CB} \to \infty$. Hence we conclude $\lim_{a_{CB}\to\infty} \lambda(a_{CB}, c) = 0$.

Second, we turn to $a_{CB} = 0$. According to (16), λ_1 then amounts to $1 + \sqrt{\frac{\sigma}{\sqrt{c}}} > 1$. Applying Equation (15) yields $\lambda(0, c) = 1$, which completes the proof.

□

G Proof of Proposition 6

We consider the cases $a_{CB} = 0$ and $a_{CB} \to \infty$ separately. First, $\lambda(a_{CB}, c) = 1$ for $a_{CB} = 0$, which is in line with Proposition 5. Substituting $\lambda = 1$ and $a_{CB} = 0$ into (14) yields the expression given in the proposition.

Second, we consider $a_{CB} \to \infty$. If $\frac{\sigma}{\sqrt{c}} < 1$, then, following the proof of Proposition 5, $\lambda(a_{CB}, c) = 0$ for sufficiently large a_{CB}. Inserting $\lambda = 0$ into (14), we obtain $L_{SOC} = 0$. The case $\frac{\sigma}{\sqrt{c}} \geq 1$ is more complex to analyze. The expression for social losses in (14) can be written as a function of $\lambda\sqrt{a_{CB}}$. Recall that $\lambda(a_{CB}, c)$ converges to zero when a_{CB} goes to infinity. It is now crucial to calculate the limit of $\lambda\sqrt{a_{CB}}$ for $a_{CB} \to \infty$.

$$\begin{aligned}
\lim_{a_{CB}\to\infty} \lambda(a_{CB}, c)\sqrt{a_{CB}} &= \lim_{a_{CB}\to\infty} \lambda_1 \sqrt{a_{CB}} \\
&= \lim_{a_{CB}\to\infty} \sqrt{a_{CB}} \frac{1+\sqrt{a_{CB}}\alpha\sqrt{\frac{\sigma}{\sqrt{c}}-1}}{1+a_{CB}\alpha^2} \\
&= \lim_{a_{CB}\to\infty} \frac{\frac{1}{\sqrt{a_{CB}}}+\alpha\sqrt{\frac{\sigma}{\sqrt{c}}-1}}{\frac{1}{a_{CB}}+\alpha^2} \\
&= \frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}}-1}.
\end{aligned}$$

Applying this finding to (14) yields

$$\begin{aligned}
\lim_{a_{CB}\to\infty} L_{SOC} &= \lim_{a_{CB}\to\infty} \frac{a_{CB}^2\alpha^2\lambda^4}{((1-\lambda)^2+a_{CB}\alpha^2\lambda^2)^2}\sigma^2 \\
&= \frac{\alpha^2\left(\frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}}-1}\right)^4}{\left(1+\alpha^2\left(\frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}}-1}\right)^2\right)^2}\sigma^2 \\
&= \frac{1}{\alpha^2}\left(\sigma-\sqrt{c}\right)^2,
\end{aligned}$$

and the proof is complete.

□

H Proof of Proposition 7

Proposition 6 shows that $\lim_{a_{CB}\to\infty} L_{SOC} = 0$ for $\sigma < \sqrt{c}$. Because social losses can never be negative, it is obvious that the social optimum is attained for $a_{CB} \to \infty$. Therefore we consider $\sigma \geq \sqrt{c}$ for the rest of the proof.

Recall that λ_1 can be written as

$$\lambda_1 = \frac{1+R}{1+a_{CB}\alpha^2} \tag{39}$$

with

$$R = \sqrt{\frac{\sigma}{\sqrt{c}} + a_{CB}\alpha^2\left(\frac{\sigma}{\sqrt{c}}-1\right)}. \tag{40}$$

For $a_{CB} < \frac{1}{\alpha^2}\frac{\sigma}{\sqrt{c}}$, we obtain $R > a_{CB}\alpha^2$, which yields $\lambda_1 > 1$ and thus, in turn, $\lambda(a_{CB}, c) = 1$ by Proposition 3. Social losses in equilibrium, which are given by (14), can then be written as

$$L_{SOC} = \frac{1}{\alpha^2}\sigma^2 + b_{SOC}c. \tag{41}$$

This expression does not depend on a_{CB}, and it is always larger than social losses for $a_{CB} \to \infty$, which are stated in Proposition 6.

It remains to consider $a_{CB} \geq \frac{1}{\alpha^2}\frac{\sigma}{\sqrt{c}}$, which implies $R \leq a_{CB}\alpha^2$ and thus $\lambda_1 \leq 1$ and $\lambda(a_{CB}, c) = \lambda_1$. We obtain

$$L_{SOC} > \frac{a_{CB}^2\alpha^2\lambda_1^4}{((1-\lambda_1)^2 + a_{CB}\alpha^2\lambda_1^2)^2}\sigma^2 = \frac{\chi^4\alpha^2}{(1+\chi^2\alpha^2)^2}\sigma^2, \tag{42}$$

where we have introduced $\chi = \sqrt{a_{CB}}\frac{\lambda_1}{1-\lambda_1}$. We note that $\frac{\chi^4\alpha^2}{(1+\chi^2\alpha^2)^2}\sigma^2$ is monotonically increasing in χ. At the end of the proof we show that χ is strictly monotonically decreasing in a_{CB}. Moreover, we will show that $\lim_{a_{CB}\to\infty}\chi = \frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}} - 1}$. These results imply

$$L_{SOC} > \frac{\chi^4\alpha^2}{(1+\chi^2\alpha^2)^2}\sigma^2 > \frac{\frac{1}{\alpha^4}\left(\frac{\sigma}{\sqrt{c}} - 1\right)^2\alpha^2}{\left(1 + \frac{1}{\alpha^2}\left(\frac{\sigma}{\sqrt{c}} - 1\right)\alpha^2\right)^2}\sigma^2 = \frac{1}{\alpha^2}(\sigma - \sqrt{c})^2. \tag{43}$$

Hence for arbitrary a_{CB} social losses are always higher than for $a_{CB} \to \infty$.

We are left with the task of showing that χ is strictly monotonically decreasing and that $\lim_{a_{CB}\to\infty}\chi = \frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}} - 1}$. We observe that

$$\begin{aligned} \chi &= \sqrt{a_{CB}}\left(\frac{\lambda_1}{1-\lambda_1}\right) \\ &= \sqrt{a_{CB}}\left(\frac{1+R}{a_{CB}\alpha^2 - R}\right). \end{aligned}$$

It is very tedious but straightforward to show that

$$\frac{\partial\chi}{\partial a_{CB}} = -\frac{1}{2}\frac{a_{CB}\alpha^2\frac{\sigma}{\sqrt{c}} + Ra_{CB}\alpha^2 + R^3 + \frac{\sigma}{\sqrt{c}}}{R(a_{CB}\alpha^2 - R)^2\sqrt{a_{CB}}}. \tag{44}$$

This expression is strictly negative. Consequently, χ is strictly monotonically decreasing. Moreover, χ can be written as follows

$$\begin{aligned}
\lim_{a_{CB}\to\infty}\chi &= \lim_{a_{CB}\to\infty}\left(\frac{\frac{1}{\sqrt{a_{CB}}}+\frac{R}{\sqrt{a_{CB}}}}{\alpha^2-\frac{R}{a_{CB}}}\right)\\
&= \frac{\lim_{a_{CB}\to\infty}\frac{1}{\sqrt{a_{CB}}}+\lim_{a_{CB}\to\infty}\frac{R}{\sqrt{a_{CB}}}}{\alpha^2-\lim_{a_{CB}\to\infty}\frac{R}{a_{CB}}}\\
&= \frac{\lim_{a_{CB}\to\infty}\frac{R}{\sqrt{a_{CB}}}}{\alpha^2}\\
&= \frac{\alpha\sqrt{\frac{\sigma}{\sqrt{c}}-1}}{\alpha^2}\\
&= \frac{1}{\alpha}\sqrt{\frac{\sigma}{\sqrt{c}}-1}.
\end{aligned}$$

To sum up, for arbitrary finite values of a_{CB}, social losses are always strictly larger than $\lim_{a_{CB}\to\infty} L_{SOC}$.

□

I Proof of Proposition 8

We distinguish between three cases. First, if $c < \frac{\sigma^2}{a_{CB}^2\alpha^4}$, then $R > a_{CB}\alpha^2$, which implies $\lambda_1 > 1$ and $\lambda(a_{CB}, c) = 1$. Second, for $\frac{\sigma^2}{a_{CB}^2\alpha^4} \leq c \leq (1 + a_{CB}\alpha^2)^2 \frac{\sigma^2}{a_{CB}^2\alpha^4}$ we obtain $R \leq a_{CB}\alpha^2$ or, equivalently, $\lambda_1 \leq 1$. Consequently, $\lambda(a_{CB}, c) = \lambda_1$, which is a monotonically decreasing function of c. Third, $c > (1 + a_{CB}\alpha^2)^2 \frac{\sigma^2}{a_{CB}^2\alpha^4}$ yields that R and thus λ_1 are not real numbers, which means that $\lambda(a_{CB}, c) = 0$. Hence $\lambda(a_{CB}, c)$ is weakly monotonically decreasing in c.

□

J Proofs of Propositions 9, 10, and 11

Proposition 9 directly follows from the proof of Proposition 8. Proposition 10 is an immediate consequence of Proposition 9 and Equation (14). Proposition 11 follows from Proposition 10 and the observation that social losses can never be negative.

□

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