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"Transparency and Reputation: Should the ECB Publish Its Inflation Forecasts?"

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Transparency and Reputation: Should the ECB Publish Its Inflation Forecasts?*

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Abstract

Recently, several central banks have abandoned the usual secrecy in monetary policy and become very transparent. This paper provides an explanation for this puzzling fact, focussing on the disclosure of central bank forecasts. It shows that transparency leads to lower inflation and gives the central bank greater flexibility to respond to shocks in the economy. Furthermore, it makes it easier for a central bank to build reputation. To achieve these benefits of transparency it is generally necessary to publish the conditional central bank forecasts for both inflation and output.

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1 Introduction

Central banks have long been associated with secrecy. Recently, however, several central banks, including the Bank of England, the Sveriges Riksbank and the Reserve Bank of New Zealand, have emphatically embraced transparency in several aspects. The move towards transparency coincided with other significant changes in their institutional or policy design, in an apparent attempt to break with relatively high inflation in the past. This is puzzling in light of the many theoretical arguments in favor of secrecy in monetary policy. One advantage of transparency is that it improves democratic accountability. However, it is not clear whether transparency has any economic benefits. This paper presents a formal argument how transparency could be beneficial for central banks and enhance their reputation. It focuses on a specific aspect of transparency, the publication of central bank forecasts. The model in this paper is especially relevant for a new or redesigned central bank, like the European Central Bank (ECB), that faces the difficult task of establishing the reputation of a strong central bank that ensures price stability.

Intuitively, the advantage of opaqueness about economic forecasts is that it limits loss of reputation for a weak central bank that prefers inflationary policy, because it obscures its true intent. However, lack of transparency could be harmful for the reputation of a strong central bank that is averse to inflation. For example, suppose the ECB reduces interest rates to stimulate the economy in response to signs of slacking output in the euro zone. If the market is unsure of the true cause, it may interpret this as a sign of inflationary policy, destroying the ECB's incipient reputation. As a result, despite the usual secretiveness in monetary policy, transparency could be useful for the ECB and improve its ability to gain reputation.

The model in this paper is in the tradition of the discretionary monetary policy games first described by Kydland and Prescott (1977) and later formalized by Barro and Gordon (1983). It is a simple two-period model with a Phillips relation and an implicit inflation target for the central bank. However, it distinguishes itself from most previous models in two respects. There is an explicit distinction between a regime of opaqueness and transparency, where the latter corresponds to the publication of conditional central bank forecasts. In addition, the model emphasizes the importance of the nominal interest rate as a signal of the central bank's intentions.

The public uses the interest rate to infer the central bank's inflation target. In the case of opaqueness, this signal is noisier and the market's inflation expectations are less responsive to the central bank's attempts to establish a reputation through higher interest rates. Thus, a central bank under opaqueness invests less in reputation, leading to higher inflation. As a result, the public prefers transparency. Since transparency has the effect of revealing the central bank's type, weak central banks would rather have opaqueness.

When the central bank cares about the variability of output, transparency has another advantage. It gives the central bank greater flexibility to respond to shocks in the economy. The reason is that the central bank is better off when the public correctly anticipates its inflation target. So, a central bank operating under opaqueness limits its stabilization efforts to make the interest rate a better signal of its type. It is forced to engage in interest rate 'smoothing' to prevent undesired effects on people's inflation expectations. As a result, opaque central banks no longer fully offset demand shocks, adding to volatility in the economy.

The conclusions of previous research related to transparency in monetary policy are mixed. Most provide explanations for secrecy, but a few have recently started to advocate openness. However, transparency is a multi-faceted concept, so I propose to distinguish the following five dimensions: (i) openness about policy objectives, like explicit inflation targets, ('political transparency'), (ii) disclosure of economic data, models and central bank forecasts ('economic transparency'), (iii) information about the monetary policy strategy and internal policy deliberations, for instance through the release of minutes and voting records ('procedural transparency'), (iv) communication of policy decisions and announcements about future actions ('policy transparency'), and (v) openness about market interventions and the implementation of policy decisions ('operational transparency', or more generally, 'market transparency'). For each of these aspects there are different motives and incentives for transparency.

This paper addresses economic transparency. Previous literature has mostly focused on political transparency, including Cukierman and Meltzer (1986), Stein (1989), Cukierman and Liviatan (1991), and Lewis (1991). They emphasize central bank private information about its unobservable objectives and they model the central bank's attempts to obfuscate shifts in preferences or to communicate its objectives, and associated credibility problems. Canzoneri (1985) and Garfinkel and Oh (1995) touch on economic transparency by considering central bank forecasts of money demand. Both assume that these forecasts are unverifiable, private information and concentrate on credibility problems. While Canzoneri (1985) accepts this information asymmetry, Garfinkel and Oh (1995) introduce noisy announcements of central bank forecasts and incorporate their effect on private sector expectations. Formal arguments regarding procedural or policy transparency are scarce. For a discussion of publication of minutes, voting records and policy directives, see Goodfriend (1986) , Buiter (1999) and Issing (1999). Operational transparency pertains to the domain of market transparency, which features a large variety of microstructure models.

Last but not least, Faust and Svensson (1999*b*) and Faust and Svensson (1999*a*) deserve special mention. They make an important contribution by introducing a theoretical distinction between imperfect monetary control and transparency, using a variation on the model by Cukierman and Meltzer (1986) with an objective function that is quadratic in both inflation and output. Transparency is incorporated in a highly abstract way. It is modeled as the extent in which a central bank 'announcement' reveals its unobservable, shifting objectives, thus ultimately providing a measure of political transparency. Although extremely useful as a benchmark, their model has several drawbacks. It is not clear whether or how their measure of transparency corresponds to the ways central banks adopt greater openness in practice, like the release of forecasts or minutes. In addition, their model is fairly complex and results are shown numerically, making it harder to identify the economic mechanisms at work. Moreover, Faust and Svensson (1999*a*) conclude that minimum transparency is a likely outcome in practice. Thus, they are not able to explain the deliberate choice for greater openness by an increasing number of central banks.

My paper contributes to the literature by providing a formal argument in favor of economic transparency. The model is tailored to the publication of central bank forecasts. In contrast to Garfinkel and Oh (1995), I do not consider credibility a fundamental issue for economic transparency. After all, the data collection, modeling and forecasting activities performed by central bank staff members could be delegated to an independent agency that reports to both the public and monetary policymakers. When the forecasts used for decision making deviate from staff forecasts and reflect policymakers' judgement, an independent monitor could attend all policy meetings and release minutes with the arguments underlying the adjustments, thereby exposing fudging of the forecasts. Thus, credibility need not be an issue.

The remainder of this paper is organized as follows. The model is presented in section 2. First, the transparency regime is analyzed in section 2.1. Subsequently, the consequences of opaqueness are derived in section 2.2 and compared to those of transparency in section 2.3. Then it is shown how economic transparency can be achieved through the publication of conditional central bank forecasts in section 2.4. Extensions to the basic model are described in section 3. Section 3.1 provides an argument how market discipline could induce all central banks to be transparent when the regime is endogenous. The model is analyzed for a quadratic central bank objective function in section 3.2 and it is shown that opaqueness induces interest rate 'smoothing'. Private incentives for secrecy may explain why many central banks shun greater openness; this is discussed in section 3.3. Finally, section 4 concludes.

2 Model

The central banker is in office for two periods and maximizes the objective function

$$U = W_1 + \delta W_2, \tag{1}$$

where δ is the subjective discount factor ($0 < \delta \leq 1$), and

$$W_t = -\frac{1}{2}\alpha\left(\pi_t - \pi^*\right)^2 + \beta\left(y_t - \bar{y}\right), \tag{2}$$

where π_t is inflation; y_t is the level of aggregate real output; π^* is the implicit inflation target, drawn from the (nondegenerate) normal distribution: $\pi^* \sim N(\tau, \sigma_\tau^2)$ with $\sigma_\tau^2 > 0$; $\bar{y}$ equals the natural rate of output; α is the importance of the inflation target ($\alpha > 0$); β is the weight on output stimulation ($\beta > 0$); and the subscript t denotes the time period, $t \in \{1, 2\}$. The economy is described by two equations. The demand for output is given by the IS relationship

$$y_t = \bar{y} - a(i_t - \pi_t^e - \bar{r}) + \varepsilon_t^d, \tag{3}$$

where i_t is the nominal interest rate; π_t^e denotes the market's inflation expectations; ε_t^d is a white noise demand shock: $\varepsilon_t^d \sim N(0, \sigma_d^2)$; $\bar{r}$ is the long-run, ex-ante real interest rate; and, a is the inverse slope of the IS curve ($a > 0$). The supply of output is given by the aggregate supply relation $y_t = \bar{y} + b(\pi_t - \pi_t^e) + \varepsilon_t^s$, or equivalently, the price adjustment equation

$$\pi_t = \pi_t^e + \frac{1}{b}(y_t - \bar{y}) - \frac{1}{b}\varepsilon_t^s, \tag{4}$$

where b is the inverse slope of the AS curve ($b > 0$), and ε_t^s is a white noise supply shock: $\varepsilon_t^s \sim N(0, \sigma_s^2)$. Assume that ε_t^s, ε_t^d and π^* are independent.

The timing is as follows. Before the first period, a regime of transparency (T) or opaqueness (O) is announced and the central bank commits to it. With transparency, the public has the same information about the shocks ε_t^d and ε_t^s as the central bank. Under opaqueness, the public remains ignorant about ε_t^d and ε_t^s. Next, the inflation target π^* is realized, but only known to the central bank. In addition, the public forms its inflation expectations π_1^e. In the first period, the central bank observes π_1^e and the economic disturbances ε_1^d and ε_1^s, and subsequently sets the nominal interest rate i_1. At the end of the first period, the public forms inflation expectations π_2^e, using the interest rate i_1 (and under transparency, ε_1^d and ε_1^s) to update its prior on π^*. At the beginning of the second period, the levels of inflation π_1 and output y_1 are observed. The central bank perceives π_2^e and the shocks ε_2^d and ε_2^s, and determines the interest rate i_2. After this last period, inflation π_2 and output y_2 are known.

Clearly, there is asymmetric information in the model. The public does not observe the central bank's inflation target π^*. In addition, it does not know the shocks ε_t^d and ε_t^s when it forms its inflation expectations π_t^e. But, under transparency, the public gets all the information that is available to the central bank when it sets the interest rate i_t, except for its implicit inflation target π^*. It is assumed that the public has rational expectations.

The problem can be solved by backwards induction. In period two, the central bank maximizes W_2 with respect to i_2 subject to (4) and (3), and given π_2^e, ε_2^d and ε_2^s. The first order condition implies

$$i_2 = \bar{r} + \pi_2^e - \frac{b}{a}\left(\pi^* + \frac{\beta b}{\alpha} - \pi_2^e\right) + \frac{1}{a}\left(\varepsilon_2^d - \varepsilon_2^s\right). \tag{5}$$

The nominal interest rate i_2 (and the ex ante real interest rate $i_2 - \pi_2^e$) is increasing in the market's inflation expectations π_2^e and the demand shock ε_2^d, but decreasing in the supply shock ε_2^s. Substituting (5) into (3) and (4) yields

$$y_2 = \bar{y} + b\left(\pi^* + \frac{\beta b}{\alpha} - \pi_2^e\right) + \varepsilon_2^s \tag{6}$$

$$\pi_2 = \pi^* + \frac{\beta b}{\alpha}. \tag{7}$$

So, output y_2 is decreasing in inflation expectations π_2^e and increasing in the output supply shock ε_2^s. The demand shock ε_2^d is completely offset by monetary policy. Since the objective function is linear in output, the supply shock ε_2^s does not affect the level of inflation π_2 and there is an inflationary bias ($\pi_2 > \pi^*$) of discretionary monetary policy. Substituting (7) and (6) into (2) gives

$$W_2 = \frac{\beta^2 b^2}{2\alpha} + \beta b\left(\pi^* - \pi_2^e\right) + \beta\varepsilon_2^s. \tag{8}$$

This shows that the central bank benefits from lower inflation expectations π_2^e. Thus, it has an incentive to improve its reputation through its actions in period one.

In the first period, the central bank maximizes the expected value of U with respect to i_1 subject to (4) and (3), given π_1^e, ε_1^d and ε_1^s, and taking into account the effect of i_1 on W_2 through π_2^e. Assume that people use the following rule to update their inflation expectations and form π_2^e based on i_1:

$$\pi_2^e = u + v i_1. \tag{9}$$

It will be shown below that this rule is consistent with a rational expectations equilibrium. Then, the first order condition with respect to i_1 implies

$$i_1 = \bar{r} + \pi_1^e - \frac{b}{a}\left(\pi^* + \frac{\beta b}{\alpha} - \pi_1^e\right) + \frac{1}{a}\left(\varepsilon_1^d - \varepsilon_1^s\right) - \frac{\delta\beta b^3}{\alpha a^2}v. \tag{10}$$

The expression for the nominal interest rate is similar to the one for the second period, except for the last term on the right-hand side. This term reflects the reputation effect of the interest rate on inflation expectations in the next period.

To show that the updating equation for inflation expectations (9) is consistent with the outcome for π_2 in (7), and to compute the values of u and v, it is necessary to distinguish between the regimes of transparency and opaqueness. Formally, the information set available to the public when it forms its inflation expectations π_1^e equals $\mathcal{T} \equiv \{T, \Omega\}$ under transparency and $\mathcal{O} \equiv \{O, \Omega\}$ under opaqueness, where $\Omega \equiv \{\alpha, \beta, a, b, \bar{y}, \bar{r}, \tau, \sigma_\tau^2, \sigma_d^2, \sigma_s^2\}$ summarizes the structure and parameters of the model. When the public forms its inflation expectations π_2^e, the available information set equals $\{i_1, \varepsilon_1^d, \varepsilon_1^s, \mathcal{T}\}$ under transparency and $\{i_1, \mathcal{O}\}$ under opaqueness. For notational convenience, denote the information sets at the end of period one excluding the interest rate by $\mathcal{T}_1 \equiv \{\varepsilon_1^d, \varepsilon_1^s, \mathcal{T}\}$ and $\mathcal{O}_1 \equiv \mathcal{O}$.

In both regimes $R \in \{T, O\}$, rational expectations imply $(\pi_2^e)^R = \mathrm{E}[\pi_2 | i_1, \mathcal{R}_1]$, where $\mathcal{R}_1 \in \{\mathcal{T}_1, \mathcal{O}_1\}$. Using (7) and the fact that i_1 in (10) is normally distributed because it depends on π^* (and under opaqueness, on the unobserved ε_1^d and ε_1^s) gives

$$(\pi_2^e)^R = \mathrm{E}[\pi^* | \mathcal{R}_1] + \frac{\mathrm{Cov}\{\pi^*, i_1 | \mathcal{R}_1\}}{\mathrm{Var}[i_1 | \mathcal{R}_1]}\left(i_1^R - \mathrm{E}[i_1 | \mathcal{R}_1]\right) + \frac{\beta b}{\alpha}. \tag{11}$$

Comparing transparency with opaqueness, the only difference is that in the case of transparency the public observes the economic disturbances to which the central bank reacts. In section 2.4 it will be shown how this notion of economic transparency can be implemented through the publication of conditional central bank forecasts in period one. But first, the outcome under transparency is needed.

2.1 Transparency

Under a regime of transparency, indicated by superscript T, the public knows i_1, ε_1^d and ε_1^s when it forms its inflation expectations π_2^e. It can therefore infer the inflation target π^* (ex post) from (10). So, using rational expectations and (7),

$$\left(\pi_2^e\right)^T = \pi^* + \frac{\beta b}{\alpha}. \tag{12}$$

Substituting (12) into (5), (6) and (7) gives the interest rate, output and inflation in the second period:

$$\begin{aligned} i_2^T &= \bar{r} + \pi^* + \frac{\beta b}{\alpha} + \frac{1}{a}\left(\varepsilon_2^d - \varepsilon_2^s\right) && (13)\\ y_2^T &= \bar{y} + \varepsilon_2^s && (14)\\ \pi_2^T &= \pi^* + \frac{\beta b}{\alpha}. && (15) \end{aligned}$$

To get the outcomes in the first period, the reputation coefficient v must be computed. Under transparency, using (10) and matching coefficients between (11) and (9) yields[1]

$$v^T = -\frac{a}{b}. \tag{16}$$

The negative value of v^T indicates that the central bank can invest in reputation by increasing i_1 to reduce π_2^e. Furthermore, using (10), (11) reduces to (12), thus establishing that this is indeed a rational expectations equilibrium.[2] [3] The first-period outcomes are obtained by substituting v^T into (10), using (3) and (4), and imposing rational expectations, $\left(\pi_1^e\right)^T = \mathrm{E}\left[\pi_1|\mathcal{T}\right]$. This produces

$$\begin{aligned} i_1^T &= \bar{r} + \mathrm{E}\left[\pi^*|\mathcal{T}\right] - \frac{b}{a}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right) + (1-\delta)\frac{\beta b}{\alpha} + \frac{1}{a}\left(\varepsilon_1^d - \varepsilon_1^s\right) && (17)\\ y_1^T &= \bar{y} + b\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right) + \varepsilon_1^s && (18)\\ \pi_1^T &= \pi^* + (1-\delta)\frac{\beta b}{\alpha}. && (19) \end{aligned}$$

[1] For completeness, $u^T = \frac{a+b}{b}\left(\pi_1^e\right)^T + \frac{a}{b}\bar{r} + \frac{\delta\beta b}{\alpha} + \frac{1}{b}\left(\varepsilon_1^d - \varepsilon_1^s\right)$.

[2] Equation (12) may give the impression that $v^T = 0$ is also a solution. However, π^* is not directly observable; it can only be inferred indirectly from i_1, ε_1^d and ε_1^s.

[3] Multiple rational expectations equilibria may exist. However, this is the only one that satisfies the McCallum (1983) criterion to employ a minimal set of state variables in the updating equation.

The first period is different from the second period for two reasons: There is a reputation effect in period one, and transparency yields $\mathrm{E}[\pi^*|\mathcal{T}_1] = \pi^*$ in period two. Regarding the latter, the uncertainty about the central bank's inflation target makes the level of output in the first period dependent on the central bank's type. A higher inflation target π^* reduces the interest rate and thereby increases output in period one.

The effect of reputation is to decrease both the nominal interest rate and inflation in period one. The effect on the interest rate may seem counter-intuitive. However, for a given level of inflation expectations π_1^e, the central bank chooses a higher (nominal and ex ante real) interest rate, and thereby lower output and lower inflation, in period one to reduce inflation expectations in period two. The lower level of inflation in period one is anticipated and reduces inflation expectations π_1^e. This decreases the (nominal and ex ante real) interest rate. Rational expectations ensure that there is no net effect on the ex ante real interest rate so that the negative effect on output in period one is completely offset. As a result, lower inflation expectations give rise to a lower nominal interest rate in period one. The effect of reputation on inflation is more familiar. Although the ex ante real interest rate is the same, the lower level of inflation expectations π_1^e reduces the level of inflation, at least partly eliminating the inflationary bias of discretionary monetary policy: $\pi^* \leq \pi_1^T < \pi_2^T$.

Substituting (12) into (8), and using (19) and (18), the expected payoff to the central bank in the case of transparency equals

$$\mathrm{E}[U|\pi^*, \mathcal{T}] = -\left(1 - \delta + \delta^2\right)\frac{\beta^2 b^2}{2\alpha} + \beta b\left(\pi^* - \mathrm{E}[\pi^*|\mathcal{T}]\right). \tag{20}$$

It shows that the central bank's expected payoff is decreasing in the inflation target expected by the public, $\mathrm{E}[\pi^*|\mathcal{T}]$.

2.2 Opaqueness

To appreciate the benefits of transparency it is important to look at the case of opaqueness as well. Under a regime of opaqueness, indicated by superscript

O, using (10) and matching coefficients between (11) and (9) yields[4]

$$v^O = -\frac{b^2\sigma_\tau^2}{b^2\sigma_\tau^2+\sigma_d^2+\sigma_s^2}\frac{a}{b} = -\lambda\frac{a}{b}, \tag{21}$$

where $\lambda \equiv \frac{b^2\sigma_\tau^2}{b^2\sigma_\tau^2+\sigma_d^2+\sigma_s^2}$. Note that $0<\lambda<1$, so compared with transparency, $\left|v^O\right| < \left|v^T\right|$. A lower interest rate has a smaller effect on π_2^e under opaqueness because people cannot tell whether it reflects a weak central bank (high π^*), or either a negative demand shock (low ε_1^d) or positive supply shock (high ε_1^s). The signal i_1 is noisier so the optimal response to it is smaller. In the limiting case $(\sigma_d^2+\sigma_s^2)\to 0$, it follows that $\lambda \to 1$; the absence of uncertainty about the disturbances ε_1^d and ε_1^s in period two gives the same outcome for v as under transparency.[5]

Using (10), (11) amounts to

$$(\pi_2^e)^O = \pi^* + \frac{\beta b}{\alpha} - (1-\lambda)(\pi^* - \mathrm{E}[\pi^*|\mathcal{O}]) - \lambda\frac{1}{b}\left(\varepsilon_1^d - \varepsilon_1^s\right). \tag{22}$$

This shows that a positive net demand shock has a beneficial effect on reputation under opaqueness, because rational agents partly attribute the rise in interest rates to a low inflation target π^* and reduce their inflation expectations correspondingly. In addition, the central bank enjoys lower inflation expectations π_2^e when its inflation target is higher than expected, because the public believes that the lower level of interest rates is due to negative net demand shocks instead.

The first-period outcomes are obtained by substituting v^O into (10), using (3) and (4), and imposing rational expectations, $(\pi_1^e)^O = \mathrm{E}[\pi_1|\mathcal{O}]$. This produces

$$i_1^O = \bar{r} + \mathrm{E}[\pi^*|\mathcal{O}] - \frac{b}{a}(\pi^* - \mathrm{E}[\pi^*|\mathcal{O}]) + (1-\lambda\delta)\frac{\beta b}{\alpha} + \frac{1}{a}\left(\varepsilon_1^d - \varepsilon_1^s\right) \tag{23}$$

$$y_1^O = \bar{y} + b(\pi^* - \mathrm{E}[\pi^*|\mathcal{O}]) + \varepsilon_1^s \tag{24}$$

$$\pi_1^O = \pi^* + (1-\lambda\delta)\frac{\beta b}{\alpha}. \tag{25}$$

[4]For completeness, $u^O = \lambda\left(\frac{a+b}{b}(\pi_1^e)^O + \frac{a}{b}\bar{r} + \lambda\delta\frac{\beta b}{\alpha}\right) + (1-\lambda)\left(\mathrm{E}[\pi^*|\mathcal{O}] + \frac{\beta b}{\alpha}\right)$.

[5]Notice that $\lambda \to 1$ is not sufficient to get the same expression for u^O, and thereby $(\pi_2^e)^O$, as under transparency. This is due to a difference in the information sets at the end of the first period: $\mathrm{E}\left[\varepsilon_1^d|\mathcal{O}_1\right] = \mathrm{E}\left[\varepsilon_1^s|\mathcal{O}_1\right] = 0$, whereas $\mathrm{E}\left[\varepsilon_1^d|\mathcal{T}_1\right] = \varepsilon_1^d$ and $\mathrm{E}\left[\varepsilon_1^s|\mathcal{T}_1\right] = \varepsilon_1^s$.

These expressions are similar to those under transparency, (17), (18) and (19), except that under opaqueness the discount factor is effectively reduced from δ to $\lambda\delta$. To facilitate comparison, use the fact that $\mathrm{E}[\pi^*|\mathcal{O}] = \mathrm{E}[\pi^*|\mathcal{T}]$ because the regime is exogenous and independent of the central bank's type. Then, the nominal interest rate in period one is higher than under transparency ($i_1^O > i_1^T$), but monetary policy is more expansionary in the sense that it leads to higher inflation ($\pi_1^O > \pi_1^T$). These seemingly contradictory results are due to the higher level of inflation expectations π_1^e under opaqueness. For given initial inflation expectations, $(\pi_1^e)^T = (\pi_1^e)^O$, the nominal (and ex ante real) interest rate is lower ($i_1^O < i_1^T$) and output is higher ($y_1^O > y_1^T$) under opaqueness. The reason is that higher interest rates do not reduce inflation expectations π_2^e as much under opaqueness because the signal is considered noisier. So, the reputation effect v of higher interest rates is diminished under opaqueness, giving rise to more expansionary monetary policy. People anticipate the higher level of inflation so that $(\pi_1^e)^O > (\pi_1^e)^T$. Thus, the central bank sets a higher level of the first-period (nominal and ex ante real) interest rate under opaqueness to contain inflation. Rational expectations ensure that the ex ante real interest rates are the same in both cases so that the levels of output are constant across the (random) regimes. Consequently, opaqueness brings about a higher first-period nominal interest rate. Although the ex ante real interest rate is the same in both cases, the higher level of inflation expectations exerts its influence. As a result, opaqueness leads to higher first-period inflation than under transparency: $\pi^* < \pi_1^T < \pi_1^O < \pi_2^T = \pi_2^O$.[6]

The analogy with the reputation argument in section 2.1 is striking. It appears that the adoption of transparency and investment in reputation have a similar effect. Both give rise to lower inflation. Moreover, transparency makes investment in reputation more fruitful. It allows the public to identify the central bank's efforts to stabilize economic shocks, which produces a more accurate signal of the central bank's type. Thus, transparency makes it more enticing for the central bank to invest in reputation, resulting in lower inflation than under opaqueness.

[6] The result that opaqueness leads to higher inflation is very robust. A sufficient condition is that $v^T < v^O$ and it is independent of the way inflation expectations are formed.

To complete the analysis of opaqueness, substitute (22) into (8), and use (25) and (24) to get the expected payoff for the central bank

$$\mathrm{E}\left[U|\pi^*,\mathcal{O}\right] = -\left(1-(2\lambda-1)\,\delta+\lambda^2\delta^2\right)\frac{\beta^2 b^2}{2\alpha}+\left(1+(1-\lambda)\,\delta\right)\beta b\left(\pi^*-\mathrm{E}\left[\pi^*|\mathcal{O}\right]\right). \tag{26}$$

Again, the expected payoff is decreasing in the expected inflation target $\mathrm{E}\left[\pi^*|\mathcal{O}\right]$.

2.3 Comparison

The analysis of opacity above shows that inflation is lower under transparency ($\pi_1^T < \pi_1^O$) but independent of economic shocks in both cases, and that the expected value of output conditional on the regime is equal ($\mathrm{E}\left[y_1^T|\mathcal{T}\right] = \mathrm{E}\left[y_1^O|\mathcal{O}\right]$). This suggests that if the public shares the central bank's objective function (2), then it would prefer transparency. Using (20) and (26), the expected payoffs for the public, which is ignorant of the central bank's inflation target π^*, equal

$$\begin{aligned}\mathrm{E}\left[U|\mathcal{T}\right] &= -\left(1-\delta+\delta^2\right)\frac{\beta^2 b^2}{2\alpha}\\ \mathrm{E}\left[U|\mathcal{O}\right] &= -\left(1-(2\lambda-1)\,\delta+\lambda^2\delta^2\right)\frac{\beta^2 b^2}{2\alpha}.\end{aligned}$$

It follows that $\mathrm{E}\left[U|\mathcal{T}\right] > \mathrm{E}\left[U|\mathcal{O}\right]$ if and only if $\left(2-(1+\lambda)\,\delta\right)(1-\lambda)\,\delta > 0$. So, indeed, the public always prefers transparency.

However, central banks do not necessarily agree with the desirability of transparency. Because the regime is exogenous so that $\mathrm{E}\left[\pi^*|\mathcal{T}\right] = \mathrm{E}\left[\pi^*|\mathcal{O}\right] = \bar{\pi}^*$, (20) and (26) imply that

$$\mathrm{E}\left[U|\pi^*,\mathcal{T}\right] > \mathrm{E}\left[U|\pi^*,\mathcal{O}\right] \Leftrightarrow \left(2-(1+\lambda)\,\delta\right)\frac{\beta b}{2\alpha} > \pi^*-\bar{\pi}^*.$$

So, strong central banks with low inflation targets would be happy to publish their forecasts, whereas weak central banks with sufficiently high inflation targets would rather be enveloped by secrecy. This suggests that if central banks could choose the regime themselves, strong central banks would have a greater incentive to adopt openness. Endogeneity of the regime will be further explored in section 3.1.

2.4 Publication of Central Bank Forecasts

Now it will be clarified how the concept of transparency in this model relates to the publication of central bank forecasts. In principle, economic transparency obtains if the public has access to the same economic information that is available to the central bank when it sets the interest rate i_t, with the exception of the level of the unobservable inflation target π^*. Thus, people are able to infer the central bank's type from its actions. The role of central bank forecasts in economic transparency is to provide information on the economic disturbances ε_t^d and ε_t^s that affect the central bank's behavior.

It is important to distinguish between two kinds of forecasts, conditional forecasts that are based on the assumption of unchanged interest rates, and unconditional forecasts that incorporate changes in the policy instrument.

2.4.1 Conditional Forecasts

To specify the meaning of unchanged interest rates in the model, denote the level of the nominal interest rate at the start of period one by i_0. Without loss of generality, assume that this is the level of i_1^T when $\varepsilon_1^d = \varepsilon_1^s = 0$. So, the interest rate used for the conditional forecast, indicated by the subscript C, follows from substituting v^T into (10):

$$\left(i_1^T\right)_C = \bar{r} + \frac{a+b}{a}\left(\pi_1^e\right)^T - \frac{b}{a}\pi^* - (1-\delta)\frac{\beta b^2}{\alpha a}.$$

Since the market's inflation expectations π_1^e are formed before the central bank forecasts are released, the forecasts are not affected by it. Using (3) and (4), the conditional output and inflation forecasts in the presence of transparency equal

$$\left(y_1^T\right)_C = \bar{y} - b\left[\left(\pi_1^e\right)^T - \pi^* - (1-\delta)\frac{\beta b}{\alpha a}\right] + \varepsilon_1^d$$

and

$$\left(\pi_1^T\right)_C = \pi^* + (1-\delta)\frac{\beta b}{\alpha a} + \frac{1}{b}\left(\varepsilon_1^d - \varepsilon_1^s\right).$$

When only the conditional inflation forecast is disclosed, people observe two variables, i_1^T and $\left(\pi_1^T\right)_C$, which can be used to solve for $\varepsilon_1^d - \varepsilon_1^s$ and π^*. So, the conditional forecast for output is not needed to deduce the implicit inflation target π^* from the interest rate. It should be noted, though, that this is due to the linearity of output in the central bank objective (2). This specification makes $\varepsilon_1^d - \varepsilon_1^s$ a sufficient statistic for economic transparency, instead of ε_1^d and ε_1^s. More generally, however, the conditional forecasts for both inflation and output are needed. This gives three equations, i_1^T, $\left(y_1^T\right)_C$ and $\left(\pi_1^T\right)_C$, which can be solved for the three unknowns, ε_1^d, ε_1^s and π^*.[7]

Hence, the benefits of economic transparency can be obtained by the publication of conditional central bank forecasts.

2.4.2 Unconditional Forecasts

In the case of transparency, the unconditional forecasts of output and inflation in the first period are simply (18) and (19). The publication of merely the unconditional inflation forecast directly reveals the inflation target π^*, even without observing the interest rate i_1^T. This means that economic transparency plays no role, in the sense that knowledge of ε_1^d and ε_1^s is irrelevant and the central bank's actions do not matter. As a result, the central bank has no incentive to invest in reputation because it knows that people no longer need the interest rate to infer its type.

Thus, the benefits of economic transparency derived in the model cannot be obtained by the release of unconditional central bank forecasts.

The publication of either unconditional or conditional (inflation) forecasts results in ex post political transparency, because the market is able to infer the implicit inflation target π^*. However, there is a crucial difference between the two. With the publication of unconditional forecasts, the interest rate loses its role as a signal of the central bank's intentions, and there is no longer any benefit for the central bank to build reputation and generate lower inflation.[8] But, with the publication of conditional forecasts, the interest rate is necessary to deduce the central bank's target π^*. So, it gives the central bank the incentive to utilize the interest rate to affect market expectations, thereby improving its performance and producing lower levels of inflation.

[7] See section 3.2, which discusses the extension of the model to a central bank objective function that is quadratic in both inflation and output.

[8] Formally, $\mathrm{E}\left[\pi^* | \pi_1^T\right] = \pi^*$, so the publication of unconditional forecasts leads to $v^T = 0$. For a given π_1^e, it has the same effect as perfect ex ante political transparency ($\sigma_\tau^2 = 0$).

3 Extensions

In this section several extensions to the basic model are analyzed. First, a simple model is considered in which the transparency regime is endogenous. Second, an alternative central bank objective function that is quadratic in both inflation and output will be examined. Third, a potentially important force against transparency is discussed, bureaucratic incentives for obfuscation.

3.1 Endogenous Regime

So far, the analysis was for an exogenous regime of transparency or opaqueness. In practice, however, the regime need not be imposed by the public but could be chosen by the central bank itself. Section 2.3 indicates that the regime preferred by the central bank depends on its inflation target π^*. In particular, strong central banks favor transparency, whereas weaker types like opaqueness. But if central banks choose their own transparency regime, the market realizes this and adjusts its beliefs accordingly, so that typically $\mathrm{E}\left[\pi^*|\mathcal{T}\right] < \mathrm{E}\left[\pi^*|\mathcal{O}\right]$. Thus, one can distinguish an additional reputation effect. The market updates its expectations about the unobservable inflation target after the central bank's choice of regime. This penalizes opaque central banks, which therefore have a greater incentive to be transparent. In fact, the negative feedback from the market in response to secrecy could induce all central banks to become transparent.

To analyze the reputation effects associated with the choice of regime, consider the following simplified model. First, the inflation target π^* is drawn from a nondegenerate normal distribution, $\pi^* \sim N\left(\tau, \sigma_\tau^2\right)$ where $\sigma_\tau^2 > 0$; the realization of π^* is only observed by the central bank, but its distribution is common knowledge. Next, the central bank announces a regime of transparency or opaqueness. Then, the public forms its expectations $\mathrm{E}\left[\pi^*|\mathcal{R}\right]$ depending on the regime $R \in \{T, O\}$. This in turn affects the central bank's expected payoff, which equals

$$\mathrm{E}\left[U|\pi^*, \mathcal{R}\right] = A^R\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{R}\right]\right) + B^R, \tag{27}$$

where $0 < A^T < A^O$ and $B^O \leq B^T$. When the inflation target is higher than expected, the central bank faces a more favorable trade-off between output and inflation which increases its expected payoff. In the case of opacity, the deviation between actual and expected inflation target persists longer so that the effect on the central bank's expected payoff is larger than under transparency. In addition, (27) reflects the assumption that on average, the public is not worse off under transparency ($\mathrm{E}[U|\mathcal{O}] \leq \mathrm{E}[U|\mathcal{T}]$). These properties are consistent with the expected payoffs (20) and (26) in the exogenous regime model in section 2.[9]

The central bank chooses the regime that produces the highest expected payoff subject to the equilibrium condition that the market's expectations $\mathrm{E}[\pi^*|\mathcal{R}]$ are consistent with the central banks' choices that follow from those expectations. When the market's beliefs off the equilibrium path are also restricted to be rational, transparency is the unique, pure-strategy perfect equilibrium.[10] The proof of this result appears in appendix A.1.

Intuitively, weak central banks with high inflation targets are inclined to select opaqueness, because it obscures their true type. However, the market realizes that opaqueness signals high inflation targets, which increases $\mathrm{E}[\pi^*|\mathcal{O}]$. This loss of reputation is costly, and fewer central banks will prefer opaqueness. As it turns out, rational market expectations in combination with a normal prior distribution of π^* make transparency the optimal choice for every type.

This simple model suggests that if central banks choose the regime themselves, market discipline suffices to make every bank transparent. However, this prediction is at odds with the facts; only very few central banks are transparent. This could be due to at least three reasons. First, the maintained assumption of rationality of market expectations, both on and off the equilibrium path, may be too strong. If the public applies Bayesian updating to form its expectations, one would expect that a given situation of

[9] It should be noted that the model in section 2 becomes nonlinear under opaqueness if not all central bank types choose the same regime. However, in the case of an endogenous regime, $\partial\,\mathrm{E}[\pi^*|i,\mathcal{O}]/\partial i = (1-\upsilon(i))\frac{\mathrm{Cov}\{\pi^*,i\}}{\mathrm{Var}[i]}$ where $0 < \upsilon(i) < 1$ and $\upsilon'(i) > 0$, so the expected central bank payoff in (27) is consistent with a linearized version of that model.

[10] Without this restriction, no pure-strategy perfect equilibrium exists. Mixed equilibria, in which some central bank types randomize between transparency and opaqueness, are possible but not considered here.

secrecy unravels to the transparency equilibrium only gradually. Second, the model may be incorrect; in particular, the choice of a central bank objective function that is linear in output may be too simplistic. To investigate this possibility, a quadratic objective function is analyzed in the next subsection. Third, central bankers may have other motives for secrecy. Private incentives against openness are discussed in section 3.3.

3.2 Quadratic Central Bank Objective

One may wonder to what extent the benefits of economic transparency are specific to the central bank's objectives. So, this section analyzes the model in section 2, but for a central bank objective function that is quadratic:

$$W_t = -\frac{1}{2}\alpha\left(\pi_t - \pi^*\right)^2 - \frac{1}{2}\beta\left(y_t - \bar{y}\right)^2. \tag{28}$$

The outcomes for this specification are derived in appendix A.2. This quadratic objective function completely eliminates the reputation effect present under the linear objective (2). So, it is no longer the case that transparency enhances the investment in reputation and brings lower (first-period) inflation. In fact, with the quadratic objective, the expected value of inflation conditional on the regime is constant over time and across regimes: $\mathrm{E}\left[\pi_t|\mathcal{R}\right] = \mathrm{E}\left[\pi^*|\mathcal{R}\right]$ for $t \in \{1,2\}$ and $\mathcal{R} \in \{\mathcal{T},\mathcal{O}\}$. And so is the conditional expected value of output.

Yet, economic transparency still makes a difference and gives rise to significant benefits. The reason is that transparency induces more accurate expectations of the central bank's inflation target and that more accurate inflation expectations lead to a higher expected payoff.[11] As before, the magnitude of the effect of the interest rate i_1 on inflation expectations π_2^e is smaller under opaqueness ($\left|v^T\right| > \left|v^O\right|$), because the signal is noisier. Under transparency, the central bank's inflation target can already be perfectly inferred from its actions. But under opaqueness, the central bank has an incentive to provide a more accurate signal of its type. In its attempt to make the interest rate a better signal of its inflation target, it restrains the stabilization of economic shocks. As a result, the effect of demand shocks on

[11] For the latter, see (31) in appendix A.2.

output is no longer completely offset and the response of inflation to supply shocks is larger. More precisely,[12]

$$\begin{aligned} y_1^O &= \bar{y} + \mu \frac{\alpha a b}{\gamma}\left(1 - \frac{\delta \beta b^3}{\gamma} v^O\right)\left(\pi^* - \mathrm{E}\left[\pi^* | \mathcal{O}\right]\right) + (1-\mu)\,\varepsilon_1^d + \mu \frac{\alpha a}{\gamma} \varepsilon_1^s \\ \pi_1^O &= \mathrm{E}\left[\pi^* | \mathcal{O}\right] + \mu \frac{\alpha a}{\gamma}\left(1 - \frac{\delta \beta b^3}{\gamma} v^O\right)\left(\pi^* - \mathrm{E}\left[\pi^* | \mathcal{O}\right]\right) \\ &\quad + \frac{1}{b}(1-\mu)\,\varepsilon_1^d - \left(1 - \mu \frac{\alpha a}{\gamma}\right)\frac{1}{b}\varepsilon_1^s, \end{aligned}$$

where $\gamma \equiv a(\alpha + \beta b^2)$ and $\mu \equiv \gamma^2 / \left(\gamma^2 + \delta \alpha \beta b^4 \left(v^O\right)^2\right)$, so $0 < \mu < 1$. For comparison, in a static context (and under transparency), demand shocks affect neither output nor inflation, and the coefficients for the effect of supply shocks on output and inflation equal $\frac{\alpha a}{\gamma}$ and $-\left(1 - \frac{\alpha a}{\gamma}\right)\frac{1}{b}$, respectively.[13] But, in the case of opaqueness, the central bank lets demand shocks seep into inflation, because it tries to prevent distorting people's expectations. Similarly, its interest rate response to supply shocks is smaller, which leads to a diminished effect of supply shocks on output, but a larger effect on inflation. Thus, a central bank under opaqueness no longer fully offsets demand shocks and no longer vigorously counters supply shocks, even when those shocks are perfectly anticipated. Instead, it engages in interest rate 'smoothing'. But under transparency, central banks need not worry about the repercussions their stabilization efforts have on inflation expectations, because they know that people are able to interpret their actions correctly. Thus, transparency has the advantage that it gives central banks greater flexibility to respond to economic shocks.

To see how the publication of central bank forecasts leads to economic transparency when the objective function is quadratic, one can again distinguish between unconditional and conditional forecasts.

Assuming transparency, the unconditional forecasts of output and infla-

[12] The derivation of these equations, which correspond to (41) and (42), is in appendix A.2.

[13] This follows from (29) and (30), and for the case of transparency (36) and (37), in appendix A.2.

tion in the first period are[14]

$$
\begin{aligned}
y_1^T &= \bar{y} + \frac{\alpha}{\alpha+\beta b^2} b \left(\pi^* - (\pi_1^e)^T\right) + \frac{\alpha}{\alpha+\beta b^2}\varepsilon_1^s \\
\pi_1^T &= (\pi_1^e)^T + \frac{\alpha}{\alpha+\beta b^2}\left(\pi^* - (\pi_1^e)^T\right) - \frac{\beta b^2}{\alpha+\beta b^2}\frac{1}{b}\varepsilon_1^s.
\end{aligned}
$$

The release of both unconditional forecasts directly reveals the inflation target π^* (and ε_1^s), even without observing the interest rate i_1^T. This means that the central bank's actions do not matter.

Let the interest rate used for conditional forecasts again be the level of i_1^T when $\varepsilon_1^s = \varepsilon_1^d = 0$. Then, the conditional output and inflation forecasts under transparency equal[15]

$$
\left(y_1^T\right)_C = \bar{y} + \frac{\alpha}{\alpha+\beta b^2} b \left(\pi^* - (\pi_1^e)^T\right) + \varepsilon_1^d
$$

$$
\left(\pi_1^T\right)_C = (\pi_1^e)^T + \frac{\alpha}{\alpha+\beta b^2}\left(\pi^* - (\pi_1^e)^T\right) + \frac{1}{b}\varepsilon_1^d - \frac{1}{b}\varepsilon_1^s.
$$

In addition, people observe the interest rate

$$
i_1^T = \bar{r} + (\pi_1^e)^T - \frac{\alpha}{\alpha+\beta b^2}\frac{b}{a}\left(\pi^* - (\pi_1^e)^T\right) - \frac{\alpha}{\alpha+\beta b^2}\frac{1}{a}\varepsilon_1^s + \frac{1}{a}\varepsilon_1^d.
$$

Now, the interest rate is necessary in addition to the forecasts. This gives three equations that can be solved for ε_1^d, ε_1^s and π^*.

So, in the case of a quadratic objective function the publication of the central bank forecasts for both inflation and output is necessary to achieve transparency. The publication of either unconditional or conditional forecasts for both inflation and output results in ex post political transparency. But again, there is an important conceptual difference between the two. With the publication of unconditional forecasts, the interest rate is not needed to signal the central bank's inflation target, whereas it is a crucial ingredient to interpret the policy message conveyed by the publication of conditional forecasts. In contrast to the objective that is linear in output, the economic

[14] See (36) and (37) in appendix A.2, and use the fact that $(\pi_1^e)^T = \mathrm{E}\left[\pi^* | \mathcal{T}\right]$.

[15] These expressions are obtained by substituting v^T into (32) and using (3) and (4).

outcome is the same whether unconditional or conditional forecasts are disclosed.[16] This is due to the fact that with the quadratic objective, the static outcome obtained by the publication of unconditional forecasts coincides with the dynamic outcome produced by the release of conditional forecasts.

Given the benefits of transparency, in terms of less uncertainty about the inflation target and less volatility due to economic disturbances, it is not surprising that the public prefers transparency when the regime is exogenous. However, central banks need not agree with the choice of regime. The reason is that the central bank's expected payoff is concave in π^* and reaches a maximum at $\pi^* = \mathrm{E}[\pi^*|\mathcal{R}]$, where $\mathcal{R} \in \{\mathcal{T}, \mathcal{O}\}$.[17] For a given level of expectations, $\mathrm{E}[\pi^*|\mathcal{T}] = \mathrm{E}[\pi^*|\mathcal{O}]$, the expected payoff under opaqueness is strictly lower than under transparency. But, when $\mathrm{E}[\pi^*|\mathcal{O}]$ and $\mathrm{E}[\pi^*|\mathcal{T}]$ are sufficiently different, central banks that are close enough to the inflation target expected under opaqueness, $\mathrm{E}[\pi^*|\mathcal{O}]$, prefer to deviate from transparency. If the beliefs off the equilibrium path are not restricted, transparency may survive as a perfect equilibrium when the expected payoff is quadratic. But, when rationality is imposed on those beliefs, perfect (pure strategy) equilibria exist that feature a range of central banks types that adopt opaqueness.[18]

3.3 Bureaucratic Incentives for Obfuscation

There may be other motives for opacity. For example, like any bureaucracy, central banks may have an incentive to hide mistakes or embarrassing forecasts, or to cherish the information rents that secrecy brings, like extensive media attention (see Stiglitz 1999). Suppose that central bank officials therefore attach a cost C to transparency so that the central bank's payoff equals $U_{CB}^T = U^T - C$ under transparency and $U_{CB}^O = U^O$ under opaqueness. This is a straightforward extension of the model. For C sufficiently large, transparency will no longer be the perfect equilibrium for the linear specification in

[16]To see this, observe that the publication of unconditional forecasts leads to $v^T = 0$ and $u^T = \pi^*$, and substitute this into (32) to get the same outcome as with the publication of conditional forecasts, (36) and (37). If $\mathrm{E}[\pi^*|\mathcal{T}] = \pi^*$, these reduce to the outcomes under perfect ex ante political transparency ($\sigma_\tau^2 = 0$).

[17]See (38) and (43).

[18]See appendix A.2 for further details.

(27) and opaqueness will become more likely for the quadratic case. Clearly, such private incentives make central banks more reluctant to adopt greater openness. Unfortunately, this imposes a big cost on society.

4 Concluding Remarks

This paper has analyzed the effect of transparency in monetary policy, in particular the publication of central bank forecasts. It focuses on 'economic transparency', which gives the public access to all economic information pertinent to the central bank's decisions, with the exception of the central bank's unobservable preferences. The paper identifies two benefits of such transparency. It enhances the central bank's ability to build reputation and leads to lower inflation. In addition, it gives the central bank greater flexibility to respond to shocks in the economy. These benefits of economic transparency can be achieved through the publication of the conditional central bank forecasts of both inflation and output. Furthermore, it is shown that when the transparency regime is exogenous, society always prefers transparency. But, when the central bank is allowed to choose the regime, transparency need not be the outcome.

This paper has a clear message: Transparency helps to build reputation. So, it is likely to have significant benefits for a young central bank like the ECB. The answer to the question whether the ECB should publish its inflation forecasts is a qualified yes. The ECB could gain a lot from economic transparency, but the disclosure of inflation forecasts will generally not suffice. What is needed is the publication of its conditional forecasts for both output and inflation.

The ECB may be reluctant to disclose its internal forecasts because they are based on euro area models and statistics which have properties that are not yet completely understood. However, this only increases the importance of the publication of forecasts, because the market will face the same or even greater uncertainties, making the interpretation of the ECB's actions more difficult. Thus, it will be much harder for the ECB to establish the reputation of strong central if it does not publish its forecasts.

Another counter argument could be that the ECB should be judged on its inflation performance, not its forecasts. However, it will take several years before the ECB has established a track record. Meanwhile, the market will try to find out the ECB's commitment to low inflation by looking at its actions, changes in the interest rate. The release of conditional forecasts allows the market to interpret this signal of the ECB's intentions more accurately.

Finally, the publication of conditional forecasts is also an excellent way to improve accountability. The ECB can use them to explain the public why adjustments in interest rates are needed. After all, if monetary policy is very effective, inflation will remain subdued and the public may accuse a central bank that raises the interest rate of 'fighting ghosts' and unnecessarily depressing output. However, the conditional forecasts help to motivate the ECB's actions; they tell the public what would happen if the ECB didn't act.

So, the ECB has a lot to gain from economic transparency. Of course, economic transparency would also benefit central banks that already have a well-established reputation, like the Federal Reserve. It allows the public to infer the central bank's intentions more accurately from its actions, which contributes to greater stability in financial markets. This in turn, gives the central bank more freedom to respond to economic disturbances, providing greater stability in the economy.

A Appendix

This appendix contains the derivation of the results discussed in section 3.

A.1 Perfect Equilibrium for Endogenous Regime

This section proves that transparency is the unique, pure-strategy perfect equilibrium in the simplified model of section 3.1, when the market's beliefs off the equilibrium path are restricted to be rational. First, it is shown that opaqueness cannot be an equilibrium because central banks with low inflation targets prefer to deviate. Second, it is shown that there is no equilibrium in which some central banks decide to adopt transparency and some opaqueness. Finally, it is shown that transparency is indeed an equilibrium.

Suppose that opaqueness is a perfect equilibrium, so $\mathrm{E}[\pi^*|\mathcal{O}] = \tau$. Consider now whether it is optimal for some central banks to deviate and adopt transparency. Using (27), central banks would prefer to deviate if and only if

$$\pi^* < \frac{1}{A^O - A^T}\left(A^O \tau - A^T \,\mathrm{E}[\pi^*|\mathcal{T}] + B^T - B^O\right)$$

The central bank that would be indifferent, whose threshold inflation target is denoted by $\tilde{\tau}$, satisfies the previous equation with equality. Rational expectations imply that $\mathrm{E}[\pi^*|\mathcal{T}] = \mathrm{E}[\pi^*|\pi^* < \tilde{\tau}]$. Let $\phi(.)$ denote the probability density function of the standard normal distribution and $\Phi(.)$ the corresponding cumulative density function. Then[19]

$$\frac{\tilde{\tau}-\tau}{\sigma_\tau} = \frac{A^T}{A^O - A^T}\frac{\phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)}{\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)} + \frac{B^T - B^O}{A^O - A^T}\frac{1}{\sigma_\tau}$$

Since the right-hand side is decreasing in $(\tilde{\tau}-\tau)/\sigma_\tau$, there exists a threshold $\tilde{\tau}$ so that opaqueness cannot be a perfect equilibrium.

Suppose that there is a threshold equilibrium such that a central bank with inflation target $\tilde{\tau}$ is indifferent between transparency and opaqueness, i.e. $\mathrm{E}[U|\tilde{\tau},\mathcal{T}] = \mathrm{E}[U|\tilde{\tau},\mathcal{O}]$. Since $\mathrm{E}[U|\pi^*,\mathcal{T}]$ and $\mathrm{E}[U|\pi^*,\mathcal{O}]$ are increasing in π^* with slopes A^T and A^O, respectively, where $A^O > A^T$, it follows

[19] Recall that $\pi^* \sim N\left(\tau, \sigma_\tau^2\right)$, so that $\mathrm{E}[\pi^*|\pi^* < \tilde{\tau}] = \tau - \sigma_\tau \phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)/\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)$.

that for $\pi^* < \tilde{\tau}$ ($\pi^* > \tilde{\tau}$) the central bank prefers a regime of transparency (opaqueness). Rational expectations imply that $\mathrm{E}[\pi^*|\mathcal{T}] = \mathrm{E}[\pi^*|\pi^* < \tilde{\tau}]$ and $\mathrm{E}[\pi^*|\mathcal{O}] = \mathrm{E}[\pi^*|\pi^* > \tilde{\tau}]$.[20] Using (27) one can show that the threshold $\tilde{\tau}$ (if any) satisfies

$$\frac{\tilde{\tau}-\tau}{\sigma_\tau} = \frac{A^O}{A^O - A^T}\frac{\phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)}{1-\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)} + \frac{A^T}{A^O - A^T}\frac{\phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)}{\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)} + \frac{B^T - B^O}{A^O - A^T}\frac{1}{\sigma_\tau}$$

Note that the right-hand side is strictly positive. In addition, ϕ/Φ and $\phi/(1-\Phi)$ are both convex in $\tilde{z} \equiv (\tilde{\tau}-\tau)/\sigma_\tau$, so that the right-hand side is convex as well. Furthermore, the sum of the first two terms on the right-hand side has an asymptote of $-\frac{A^T}{A^O-A^T}\tilde{z}$ as $\tilde{z} \to -\infty$ and $\frac{A^O}{A^O-A^T}\tilde{z}$ as $\tilde{z} \to \infty$. Hence, the right-hand side is strictly greater than $\tilde{z}$ for any $\tilde{z}$. This means that no threshold equilibrium exists.

Finally, suppose that transparency is a perfect equilibrium, so $\mathrm{E}[\pi^*|\mathcal{T}] = \tau$. Consider now whether it is optimal for some central banks to deviate and adopt opaqueness. Using (27), central banks would prefer to deviate if and only if

$$\pi^* > \frac{1}{A^O - A^T}\left(A^O\,\mathrm{E}[\pi^*|\mathcal{O}] - A^T\tau + B^T - B^O\right)$$

The central bank that would be indifferent, whose inflation target is denoted by $\tilde{\tau}$, satisfies the previous equation with equality. Rational expectations imply that $\mathrm{E}[\pi^*|\mathcal{O}] = \mathrm{E}[\pi^*|\pi^* > \tilde{\tau}]$. Hence,

$$\frac{\tilde{\tau}-\tau}{\sigma_\tau} = \frac{A^O}{A^O - A^T}\frac{\phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)}{1-\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)} + \frac{B^T - B^O}{A^O - A^T}\frac{1}{\sigma_\tau}$$

Note that the right-hand side is strictly positive. Furthermore, the right-hand side is increasing and convex in $\tilde{z} \equiv (\tilde{\tau}-\tau)/\sigma_\tau$, with a horizontal asymptote of 0 as $\tilde{z} \to -\infty$ and an asymptote of $\frac{A^O}{A^O-A^T}\tilde{z}$ as $\tilde{z} \to \infty$. Hence, this equation has no solution for $\tilde{z}$, which means that there exists no threshold $\tilde{\tau}$ such that deviation from transparency is preferred. Therefore, transparency is the unique, pure-strategy perfect equilibrium.[21]

[20] Note that $\mathrm{E}[\pi^*|\pi^* > \tilde{\tau}] = \tau + \sigma_\tau\phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)/\left[1-\Phi\left(\frac{\tilde{\tau}-\tau}{\sigma_\tau}\right)\right]$.

[21] Without the restriction that beliefs off the equilibrium path (i.e. $\mathrm{E}[\pi^*|\mathcal{O}]$) are rational,

A.2 Quadratic Objective Function

This section derives the results for the quadratic central bank objective function (28). In period two, the central bank maximizes W_2 with respect to i_2 subject to (4) and (3), and given π_2^e, ε_2^d and ε_2^s. The first order condition implies

$$i_2 = \frac{b\alpha + a\left(\alpha + \beta b^2\right)}{a\left(\alpha + \beta b^2\right)}\pi_2^e - \frac{\alpha b}{a\left(\alpha + \beta b^2\right)}\pi^* + \bar{r} + \frac{1}{a}\varepsilon_2^d - \frac{\alpha}{a\left(\alpha + \beta b^2\right)}\varepsilon_2^s.$$

Using (3) and (4) this yields

$$y_2 = \bar{y} - \frac{b\alpha}{\alpha + \beta b^2}\left(\pi_2^e - \pi^*\right) + \frac{\alpha}{\alpha + \beta b^2}\varepsilon_2^s \tag{29}$$

$$\pi_2 = \pi_2^e + \frac{\alpha}{\alpha + \beta b^2}\left(\pi^* - \pi_2^e\right) - \frac{\beta b}{\alpha + \beta b^2}\varepsilon_2^s. \tag{30}$$

Substituting (29) and (30) into (28) and taking expectations gives

$$\mathrm{E}\left[W_2|\Omega, \pi_2^e\right] = -\frac{1}{2}\frac{\alpha\beta}{\alpha + \beta b^2}\left(b^2\left(\pi_2^e - \pi^*\right)^2 + \sigma_s^2\right) \tag{31}$$

So, expected wealth in period two is maximized when the market perfectly anticipates the central banks type: $\pi_2^e = \pi^*$. Thus, it is in the central bank's interest to reveal its type through its actions.

In the first period, the central bank maximizes the expected value of U with respect to i_1 subject to (4) and (3), given π_1^e, ε_1^d and ε_1^s, and assuming (9). The first order condition implies

$$\begin{aligned} i_1 = {} & \frac{\gamma^2}{\gamma^2 + \delta\alpha\beta b^4 v^2}\bar{r} + \frac{\gamma^2 + b\alpha\gamma}{\gamma^2 + \delta\alpha\beta b^4 v^2}\pi_1^e - \frac{b\alpha\gamma - \delta\alpha\beta b^4 v}{\gamma^2 + \delta\alpha\beta b^4 v^2}\pi^* \\ & - \frac{\delta\alpha\beta b^4 v}{\gamma^2 + \delta\alpha\beta b^4 v^2}u + \frac{\frac{1}{a}\gamma^2}{\gamma^2 + \delta\alpha\beta b^4 v^2}\varepsilon_1^d - \frac{\alpha\gamma}{\gamma^2 + \delta\alpha\beta b^4 v^2}\varepsilon_1^s, \end{aligned} \tag{32}$$

where $\gamma \equiv a\left(\alpha + \beta b^2\right)$.

Under either regime of transparency or opaqueness, rational expectations and (7) give, after rearranging, $\left(\pi_2^e\right)^R = \mathrm{E}\left[\pi^*|i_1, \mathcal{R}_1\right]$. Using the fact that i_1

transparency would not be a perfect equilibrium because there would always exist types with sufficiently large π^* that prefer to deviate. This is a consequence of the unbounded support of the distribution of π^*.

in (32) is normally distributed,

$$\left(\pi_2^e\right)^R = \mathrm{E}\left[\pi^*|\mathcal{R}_1\right] + \frac{\mathrm{Cov}\left\{\pi^*, i_1|\mathcal{R}_1\right\}}{\mathrm{Var}\left[i_1|\mathcal{R}_1\right]}\left(i_1^T - \mathrm{E}\left[i_1|\mathcal{R}_1\right]\right). \tag{33}$$

Under transparency, ε_1^d and ε_1^s are observed so that the market can infer π^* from i_1. Hence, (30) implies

$$\left(\pi_2^e\right)^T = \pi^*. \tag{34}$$

Using (32) and matching coefficients between (33) and (9) yields after rearranging

$$\begin{aligned} v^T &= -\frac{\gamma}{\alpha b} \\ u^T &= \frac{\gamma}{\alpha b}\bar{r} + \frac{\gamma + \alpha b}{\alpha b}\left(\pi_1^e\right)^T + \frac{\alpha + \beta b^2}{\alpha}\frac{1}{b}\varepsilon_1^d - \frac{1}{b}\varepsilon_1^s. \end{aligned}$$

Substituting this into (32), using (3) and (4), and imposing rational expectations produces

$$i_1^T = \bar{r} + \mathrm{E}\left[\pi^*|\mathcal{T}\right] - \frac{\alpha}{\alpha + \beta b^2}\frac{b}{a}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right) - \frac{\alpha}{\alpha + \beta b^2}\frac{1}{a}\varepsilon_1^s + \frac{1}{a}\varepsilon_1^d \tag{35}$$

$$y_1^T = \bar{y} + \frac{\alpha}{\alpha + \beta b^2} b\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right) + \frac{\alpha}{\alpha + \beta b^2}\varepsilon_1^s \tag{36}$$

$$\pi_1^T = \mathrm{E}\left[\pi^*|\mathcal{T}\right] + \frac{\alpha}{\alpha + \beta b^2}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right) - \frac{\beta b^2}{\alpha + \beta b^2}\frac{1}{b}\varepsilon_1^s \tag{37}$$

Substituting (34) into (31), and using (36) and (37) gives the expected payoff for the central bank

$$\mathrm{E}\left[U|\pi^*, \mathcal{T}\right] = -\frac{1}{2}\frac{\alpha\beta b^2}{\alpha + \beta b^2}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right)^2 - \frac{1}{2}\frac{\alpha\beta}{\alpha + \beta b^2}\left(1 + \delta\right)\sigma_s^2. \tag{38}$$

In the case of opaqueness, using (32) and matching coefficients between (33) and (9) gives after rearranging

$$-\delta\alpha^2\beta b^5\gamma\sigma_\tau^2\left(v^O\right)^2 + \gamma^2\left(\alpha b^2\left(\alpha - \delta\beta b^2\right)\sigma_\tau^2 + \frac{\gamma^2}{a^2}\sigma_d^2 + \alpha^2\sigma_s^2\right)v^O + \alpha b\gamma^3\sigma_\tau^2 = 0.$$

This equation has two roots, $v_1^O > 0$ and $v_2^O < 0$. However, the positive root v_1^O can be excluded based on an argument by McCallum (1983).[22] The

[22] To be precise, v_1^O is not valid for all admissible parameter values, because $\lim_{\sigma_d^2, \sigma_s^2 \to 0} v_1^O \neq v^T$.

remaining negative root can be written as

$$v^O = \frac{\gamma}{2\delta\alpha^2\beta a^2 b^5\sigma_\tau^2}\left\{\alpha^2a^2b^2\sigma_\tau^2 - \delta\alpha\beta a^2b^4\sigma_\tau^2 + \gamma^2\sigma_d^2 + \alpha^2a^2\sigma_s^2 \right.$$
$$\left. - \sqrt{\left(\alpha^2a^2b^2\sigma_\tau^2 + \delta\alpha\beta a^2b^4\sigma_\tau^2 + \gamma^2\sigma_d^2 + \alpha^2a^2\sigma_s^2\right)^2 - 4\delta\alpha\beta a^2b^4\left(\gamma^2\sigma_d^2 + \alpha^2a^2\sigma_s^2\right)\sigma_\tau^2}\right\}$$

Clearly, $v^O > -\gamma/\alpha b$. Hence, $\left|v^O\right| < \left|v^T\right|$; the magnitude of the effect of the interest rate on inflation expectations is smaller under opaqueness because it is a noisier signal of the inflation target. Note that $\lim_{\sigma_d^2,\sigma_s^2\to 0} v^O = -\frac{\gamma}{\alpha b} = v^T$. In the absence of uncertainty about the shocks, the effect of interest rates on inflation expectations is the same for opaqueness and transparency.[23]

In addition, matching coefficients gives

$$u^O = \mathrm{E}\left[\pi^*|\mathcal{O}\right] + \frac{\alpha b v^O}{\gamma}\left(\mathrm{E}\left[\pi^*|\mathcal{O}\right] - \left(\pi_1^e\right)^O\right) - v^O\left(\bar{r} + \left(\pi_1^e\right)^O\right).$$

Using (32), (33) yields

$$\begin{aligned}\left(\pi_2^e\right)^O &= \mathrm{E}\left[\pi^*|\mathcal{O}\right] - \frac{\alpha\gamma b v^O - \delta\alpha\beta b^4\left(v^O\right)^2}{\gamma^2 + \delta\alpha\beta b^4\left(v^O\right)^2}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{O}\right]\right) \\ &+ \frac{\frac{1}{a}\gamma^2 v^O}{\gamma^2 + \delta\alpha\beta b^4\left(v^O\right)^2}\varepsilon_1^d - \frac{\alpha\gamma v^O}{\gamma^2 + \delta\alpha\beta b^4\left(v^O\right)^2}\varepsilon_1^s.\end{aligned} \tag{39}$$

Substituting u^O into (32), using (3) and (4), and imposing rational expectations produces

$$i_1^O = \bar{r} + \mathrm{E}\left[\pi^*|\mathcal{O}\right] - \mu\frac{\alpha b}{\gamma}\left(1 - \frac{\delta\beta b^3}{\gamma}v^O\right)\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{O}\right]\right) + \frac{\mu}{a}\varepsilon_1^d - \frac{\alpha\mu}{\gamma}\varepsilon_1^s \tag{40}$$

$$y_1^O = \bar{y} + \mu\frac{\alpha a b}{\gamma}\left(1 - \frac{\delta\beta b^3}{\gamma}v^O\right)\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{O}\right]\right) + (1-\mu)\varepsilon_1^d + \frac{\alpha a}{\gamma}\mu\varepsilon_1^s \tag{41}$$

$$\begin{aligned}\pi_1^O &= \mathrm{E}\left[\pi^*|\mathcal{O}\right] + \mu\left(1 - \frac{\delta\beta b^3}{\gamma}v^O\right)\frac{\alpha a}{\gamma}\left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{O}\right]\right) \\ &+ \frac{1}{b}(1-\mu)\varepsilon_1^d - \left(1 - \mu\frac{\alpha a}{\gamma}\right)\frac{1}{b}\varepsilon_1^s,\end{aligned} \tag{42}$$

where $\mu \equiv \frac{\gamma^2}{\gamma^2 + \delta\alpha\beta b^4\left(v^O\right)^2}$ $(0 < \mu < 1)$. Notice that the responsiveness of the interest rate to demand and supply shocks is smaller under opaqueness.

[23] If in addition $\mathrm{E}\left[\varepsilon_1^d|\mathcal{O}_1\right] = \varepsilon_1^d$ and $\mathrm{E}\left[\varepsilon_1^s|\mathcal{O}_1\right] = \varepsilon_1^s$, u^O reduces to u^T and the outcomes under opaqueness and transparency are identical.

As a consequence, demand shocks are no longer completely offset and affect output, and thereby inflation. In addition, the magnitude of the effect of supply shocks on the level of inflation has increased from $\left(1-\frac{\alpha a}{\gamma}\right)\frac{1}{b}$ under transparency to $\left(1-\mu\frac{\alpha a}{\gamma}\right)\frac{1}{b}$ under opaqueness, and the effect on output has decreased from $\frac{\alpha a}{\gamma}$ under transparency to $\frac{\alpha a}{\gamma}\mu$ under opaqueness.

Substituting (39) into (31), and using (41) and (42) gives after some rearranging the expected payoff for the central bank

$$\begin{aligned}\mathrm{E}\left[U|\pi^*,\mathcal{O}\right] &= -\frac{1}{2}\left(1+\delta\left(1+\frac{\alpha b}{\gamma}v^O\right)^2\mu\right)\frac{\alpha a\beta b^2}{\gamma}\left(\pi^*-\mathrm{E}\left[\pi^*|\mathcal{O}\right]\right)^2 \\ &\quad -\frac{1}{2}\frac{\gamma}{ab^2}\left(1-\mu\right)\sigma_d^2-\frac{1}{2}\frac{\alpha a\beta}{\gamma}\left(1+\left(1+\frac{\alpha^2b^2\left(v^O\right)^2}{\gamma^2}\mu\right)\delta\right)\sigma_s^2\end{aligned} \qquad (43)$$

Comparing (38) and (43), the expected payoff for a central bank with inflation target π^* in regime $R\in\{T,O\}$ equals

$$\mathrm{E}\left[U|\pi^*,\mathcal{R}\right]=A_1^R\left(\pi^*-\mathrm{E}\left[\pi^*|\mathcal{R}\right]\right)^2+A_2^R\sigma_d^2+A_3^R\sigma_s^2$$

where $\mathcal{R}\in\{\mathcal{T},\mathcal{O}\}$,

$$\begin{aligned}A_1^T &= -\frac{1}{2}\frac{\alpha a\beta b^2}{\gamma} \\ A_2^T &= 0 \\ A_3^T &= -\frac{1}{2}\frac{\alpha a\beta}{\gamma}\left(1+\delta\right)\end{aligned}$$

and[24]

$$\begin{aligned}A_1^O &= -\frac{1}{2}\left(1+\delta\left(1+\frac{\alpha b}{\gamma}v^O\right)^2\mu\right)\frac{\alpha a\beta b^2}{\gamma} \\ A_2^O &= -\frac{1}{2}\frac{\gamma}{ab^2}\left(1-\mu\right) \\ A_3^O &= -\frac{1}{2}\frac{\alpha a\beta}{\gamma}\left(1+\left(1+\frac{\alpha^2b^2\left(v^O\right)^2}{\gamma^2}\mu\right)\delta\right).\end{aligned}$$

[24]Note that substituting v^T for v^O in A_1^O gives A_1^T. This does not hold for A_2^O and A_3^O, however, because those are affected by an additional difference; $\mathrm{E}\left[\varepsilon_1^d|\mathcal{T}_1\right]=\varepsilon_1^d$ and $\mathrm{E}\left[\varepsilon_1^s|\mathcal{T}_1\right]=\varepsilon_1^s$, whereas $\mathrm{E}\left[\varepsilon_1^d|\mathcal{O}_1\right]=0$ and $\mathrm{E}\left[\varepsilon_1^s|\mathcal{O}_1\right]=0$.

Observe that $0 > A_1^T > A_1^O$ because $v^O > -\gamma/\alpha b$, and that $0 > A_2^T > A_2^O$ and $0 > A_3^T > A_3^O$ because $0 < \mu < 1$. The expected payoff for the public equals

$$\mathrm{E}\left[U|\mathcal{R}\right] = A_1^R \operatorname{Var}\left[\pi^*|\mathcal{R}\right] + A_2^R \sigma_d^2 + A_3^R \sigma_s^2.$$

So, if the regime is exogenous and randomly assigned so that $\operatorname{Var}\left[\pi^*|\mathcal{T}\right] = \operatorname{Var}\left[\pi^*|\mathcal{O}\right]$, transparency is preferred: $\mathrm{E}\left[U|\mathcal{O}\right] < \mathrm{E}\left[U|\mathcal{T}\right]$.

When the regime is endogenous, the expected payoff to the central bank can be written as[25]

$$\mathrm{E}\left[U|\pi^*, \mathcal{R}\right] = A^R \left(\pi^* - \mathrm{E}\left[\pi^*|\mathcal{R}\right]\right)^2 + B^R$$

where $A^O < A^T < 0$ and $B^O < B^T$. This is a parabola in π^* with a maximum of B^R at $\pi^* = \mathrm{E}\left[\pi^*|\mathcal{R}\right]$. Observe that for $\mathrm{E}\left[\pi^*|\mathcal{T}\right] = \mathrm{E}\left[\pi^*|\mathcal{O}\right]$, every central bank prefers transparency. But when $\mathrm{E}\left[\pi^*|\mathcal{O}\right]$ is sufficiently different from $\mathrm{E}\left[\pi^*|\mathcal{T}\right]$, a range of inflation targets around $\mathrm{E}\left[\pi^*|\mathcal{O}\right]$ exists where central banks are better off with opaqueness.

To find a perfect equilibrium, suppose there are thresholds $\underline{\tau}$ and $\bar{\tau}$ ($\underline{\tau} < \bar{\tau}$) such that central banks at $\underline{\tau}$ and $\bar{\tau}$ are indifferent between transparency and opaqueness: $\mathrm{E}\left[U|\underline{\tau}, \mathcal{T}\right] = \mathrm{E}\left[U|\underline{\tau}, \mathcal{O}\right]$ and $\mathrm{E}\left[U|\bar{\tau}, \mathcal{T}\right] = \mathrm{E}\left[U|\bar{\tau}, \mathcal{O}\right]$. This implies that central banks with $\pi^* < \underline{\tau}$ and $\bar{\tau} < \pi^*$ prefer transparency and those with $\underline{\tau} < \pi^* < \bar{\tau}$ prefer opaqueness. Hence, using the fact that $\pi^* \sim N\left(\tau, \sigma_\tau^2\right)$,

$$\begin{aligned}
\mathrm{E}\left[\pi^*|\mathcal{T}\right] &= \mathrm{E}\left[\pi^*|\pi^* < \underline{\tau}, \bar{\tau} < \pi^*\right] = \tau + \sigma_\tau \frac{\phi\left(\frac{\bar{\tau}-\tau}{\sigma_\tau}\right) - \phi\left(\frac{\underline{\tau}-\tau}{\sigma_\tau}\right)}{1 - \Phi\left(\frac{\bar{\tau}-\tau}{\sigma_\tau}\right) + \Phi\left(\frac{\underline{\tau}-\tau}{\sigma_\tau}\right)} \\
\mathrm{E}\left[\pi^*|\mathcal{O}\right] &= \mathrm{E}\left[\pi^*|\underline{\tau} < \pi^* < \bar{\tau}\right] = \tau - \sigma_\tau \frac{\phi\left(\frac{\bar{\tau}-\tau}{\sigma_\tau}\right) - \phi\left(\frac{\underline{\tau}-\tau}{\sigma_\tau}\right)}{\Phi\left(\frac{\bar{\tau}-\tau}{\sigma_\tau}\right) - \Phi\left(\frac{\underline{\tau}-\tau}{\sigma_\tau}\right)}
\end{aligned}$$

Substituting and rearranging, the threshold $\underline{\tau}$ solves

$$\begin{aligned}
A^T \left(\underline{\tau} - \mathrm{E}\left[\pi^*|\mathcal{T}\right]\right)^2 + B^T &= A^O \left(\underline{\tau} - \mathrm{E}\left[\pi^*|\mathcal{O}\right]\right)^2 + B^O \\
\sigma_\tau^2 A^T \left(\underline{z} - \frac{\phi\left(\bar{z}\right) - \phi\left(\underline{z}\right)}{1 - \Phi\left(\bar{z}\right) + \Phi\left(\underline{z}\right)}\right)^2 + B^T &= \sigma_\tau^2 A^O \left(\underline{z} + \frac{\phi\left(\bar{z}\right) - \phi\left(\underline{z}\right)}{\Phi\left(\bar{z}\right) - \Phi\left(\underline{z}\right)}\right)^2 + B^O
\end{aligned}$$

[25]The same caveat applies as in footnote 9.

where $\underline{z} \equiv (\underline{\tau} - \tau)/\sigma_\tau$ and $\bar{z} \equiv (\bar{\tau} - \tau)/\sigma_\tau$. The corresponding condition for the threshold $\bar{\tau}$ is

$$\sigma_\tau^2 A^T \left(\bar{z} - \frac{\phi(\bar{z}) - \phi(\underline{z})}{1 - \Phi(\bar{z}) + \Phi(\underline{z})} \right)^2 + B^T = \sigma_\tau^2 A^O \left(\bar{z} + \frac{\phi(\bar{z}) - \phi(\underline{z})}{\Phi(\bar{z}) - \Phi(\underline{z})} \right)^2 + B^O$$

Thus, finding a perfect equilibrium with thresholds $\underline{\tau}$ and $\bar{\tau}$ (if any) amounts to finding two solutions for z, z_1 and z_2 ($z_1 > z_2$), to the equation

$$\sigma_\tau^2 A^T \left(z - \frac{\phi(\bar{z}) - \phi(\underline{z})}{1 - \Phi(\bar{z}) + \Phi(\underline{z})} \right)^2 + B^T = \sigma_\tau^2 A^O \left(z + \frac{\phi(\bar{z}) - \phi(\underline{z})}{\Phi(\bar{z}) - \Phi(\underline{z})} \right)^2 + B^O \tag{44}$$

subject to the condition that $z_1 = \bar{z}$ and $z_2 = \underline{z}$. Denote this threshold equilibrium by $\{\underline{z}, \bar{z}\}$.

Note that if a threshold equilibrium$\{\underline{z}, \bar{z}\}$ exists, then $\{-\bar{z}, -\underline{z}\}$ is also an equilibrium. So, (pure strategy) threshold equilibria always come in symmetric pairs. This is not surprising given the symmetry of the problem when the objective function is quadratic in output. In addition, it is easy to see that $\{-z, z\}$ cannot be an equilibrium. Suppose it is, then $\sigma_\tau^2 \left(A^T - A^O\right) z^2 = -\left(B^T - B^O\right) < 0$, which leads to a contradiction.

Pairs of threshold equilibria can be computed numerically using (44). This tends to give a unique pair of threshold equilibria. However, when the difference between B^T and B^O becomes very large, the magnitude of $\underline{z}$ and $\bar{z}$ gives rise to numerical problems with the evaluation of the densities and no equilibrium can be found.

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