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Optimal monetary policy in a hybrid New Keynesian model with a cost channel

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Optimal monetary policy in a hybrid New Keynesian model with a cost channel

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Abstract

This study shows that an expectations-based optimal policy rule has desirable properties in a standard macroeconomic model incorporating a cost channel for monetary disturbances and inflation rate expectations that are partly backward-looking. Specifically, optimal monetary policy under commitment is associated with a determinate REE that is stable under learning, whereas, under discretion, the central bank has to be sufficiently inflation averse for the equilibrium to have these properties.

Keywords: commitment, determinacy, discretion, expectations-based rule, least squares learning

JEL classification numbers: E52, E61

Optimaalinen korko-ohjaus ja rahapolitiikan kustannuskanava osittain eteenpäin katsovassa dynaamisessa rahapolitiikan makromallissa

Suomen Pankin keskustelualoitteita 24/2007

Mikael Bask
Rahapolitiikka- ja tutkimusosasto

Tiivistelmä

Tässä tutkimuksessa osoitetaan, että ennustetietoon perustuvalla rahapolitiikan korkosäännöllä on talouden tasapainottumisen kannalta hyviä ominaisuuksia rahapolitiikan dynaamisessa makromallissa, jossa rahapolitiikan vaikutukset välittyvät yritysten tuotantokustannusten kautta ja jossa odotustenmuodostus on osittain menneeseen katsovaa. Työssä täsmällisemmin sanoen osoitetaan, että sitoutuminen rahapolitiikassa – eli yksityisen sektorin odotusten yhdistäminen keskuspankin politiikkavalmisteluun – on tasapainon määräytyneisyyden ja odotustenmuodostuksen pitkän aikavälin rationaalisuuden kannalta tärkeää. Toisaalta nämä tasapainon ominaisuudet – määräytyneisyys ja odotustenmuodostuksen harhattomuus – toteutuvat harkinnanvaraisen rahapolitiikan oloissa, jolloin keskuspankki ei ota huomioon politiikkatoimenpiteidensä odotusvaikutuksia, vain jos keskuspankki on riittävän inflaationvastainen.

Avainsanat: sitoutuminen, määräytyneisyys, harkinnanvaraisuus, odotuksiin perustuva ohjaussääntö, pienimmän neliösumman oppiminen

JEL-luokittelu: E52, E61

Contents

1 Introduction

To overcome the problem with the indeterminacy of REE that is a typical result when an optimal policy rule for the central bank is implemented in a standard macroeconomic model, Evans and Honkapohja (2003a–c, 2006) argue that the interest rate rule should be implemented as an expectations-based rule. This is because such a rule does not impose rational expectations on behalf of agents, but, instead, incorporate their private expectations into the rule. As a result, there is a mechanism that can correct these expectations so that the economy ends up in a REE that also is unique.

What we do in this paper is to examine if an expectations-based rule still have desirable properties after extending a standard model in two directions. The first is to include a cost channel into the model since Barth and Ramey (2001) and Chowdhury et al (2006) provide empirical evidence for such a channel. That is, they found evidence that firms' marginal costs are directly affected by the interest rate. The intuition is that firms have to pay their production factors before they receive revenues from selling their products, and, therefore, need to borrow money from financial intermediaries.

Another empirical finding is that there is persistence in inflation rates (see Altissimo et al, 2006, for references for the euro area). Thus, several authors have found that the presence of the lagged inflation rate improves the ability of empirical models to explain observed inflation rate dynamics. Therefore, a hybrid new Keynesian model is sometimes used as the theoretical framework in policy-making, meaning that the expected inflation rate is a weighted average of the lagged inflation rate and the inflation rate under rational expectations. In this paper, we do the same extension in a standard model.

Despite the argument that the empirical relevance of the cost channel is small and that there is an apparent tension between observed inflation rate dynamics and theoretical models based on optimizing behavior, we study optimal monetary policy in a new Keynesian model that includes a cost channel for monetary disturbances and the lagged inflation rate. Thus, we derive interest rate rules for the central bank that implement optimal policy, both under discretion and commitment, and examine under what conditions the economy is characterized by a unique and learnable REE.

2 Model

The model consists of an IS curve and an AS curve with a cost channel for monetary disturbances in the spirit of Ravenna and Walsh (2006)

$$\begin{cases} x_t = E_t\left[x_{t+1}\right] - \alpha\left(r_t - E_t^*\left[\pi_{t+1}\right]\right) \\ \pi_t = \beta E_t^*\left[\pi_{t+1}\right] + \gamma x_t + \delta r_t + \varepsilon_t \end{cases} \tag{2.1}$$

where the expected inflation rate is

$$E_t^*\left[\pi_{t+1}\right] = \omega\pi_{t-1} + (1-\omega)\, E_t\left[\pi_{t+1}\right] \tag{2.2}$$

and $\omega \in [0, 1]$ is the importance of the lagged inflation rate in the expectations formation process. Moreover, x_t is the output gap, r_t is the interest rate that is controlled by the central bank, π_t is the inflation rate, and ε_t is a cost-push shock. Finally, $E_t[\cdot]$ is the mathematical expectation of the variable in focus, conditioned on the structure of the complete model as well as realized values of all variables in the model up to and including time t.

Even though there is an endogenous cost channel in the AS curve, we also incorporate exogenous cost-push shocks into the model to allow for impulses to the economy. However, $\varepsilon_t \equiv 0$ would not affect our findings. Moreover, even though the current inflation rate is included in the agents' information set, we make use of the lagged inflation rate in the expectations formation process since we would like to examine the properties of the model using a hybrid specification of the new Keynesian Phillips curve (see Galí and Gertler, 1999, for a derivation of this curve).

3 Optimal monetary policy

The model in (2.1)–(2.2) is closed by deriving an interest rate rule for the central bank that minimizes an objective function that translates the target variables' behavior into a welfare measure

$$\mathbf{W}_t = -E_t \sum\nolimits_{i=0}^{\infty} \beta^i \left(\zeta x_{t+i}^2 + \pi_{t+i}^2\right) \tag{3.1}$$

where ζ is the flexibility in inflation rate targeting that is restricted to $\zeta \in [0,1]$ when the properties of the model are examined. As will be clear below, this is not an important restriction from the point of view of optimal policy-making. Moreover, since we have neglected from fiscal shocks in the IS curve, the welfare measure in (3.1) coincides with the measure derived in Ravenna and Walsh (2006). Specifically, their measure is a second-order approximation of the representative household's utility function.

The Lagrangian at time $t = 0$ is

$$\begin{aligned}\mathbf{L}_0 \quad = \quad & -E_0 \sum\nolimits_{i=0}^{\infty} \beta^i \{\zeta x_i^2 + \pi_i^2 - \lambda_i \pi_i \\ & +\lambda_i \left((\beta+\delta)\, \omega \pi_{i-1} + (\beta+\delta)(1-\omega)\, \pi_{i+1} \right) \\ & +\lambda_i \left(-\left(\frac{\delta}{\alpha} - \gamma\right) \cdot x_i + \frac{\delta}{\alpha} \cdot x_{i+1} + \varepsilon_i \right) \}\end{aligned} \tag{3.2}$$

where the constraint in the optimization problem is the economy's law of motion in (2.1)–(2.2).[1] Thus, the first-order conditions when there is discretion in policy-making are

$$\begin{cases} x_t : & 2\zeta x_t - \left(\frac{\delta}{\alpha} - \gamma\right) \cdot \lambda_t = 0 \\ \pi_t : & 2\pi_t - \lambda_t + \beta (\beta+\delta)\, \omega \lambda_{t+1} = 0 \end{cases} \tag{3.3}$$

However, instead of optimizing the objective function in each time period, the central bank can do better by solving for the first-order conditions that

[1] In the Technical Appendix, derivations of several of the equations in this paper can be found, including the constraint in (3.2).

support a policy that is optimal over time. In this case, the Lagrangian has the following first-order conditions

$$\begin{cases} x_t: & \frac{\delta}{\alpha}\cdot\lambda_{t-1}+2\beta\zeta x_t-\beta\left(\frac{\delta}{\alpha}-\gamma\right)\cdot\lambda_t=0 \\ \pi_t: & \left(\beta+\delta\right)\left(1-\omega\right)\lambda_{t-1}+2\beta\pi_t-\beta\lambda_t+\beta^2\left(\beta+\delta\right)\omega\lambda_{t+1}=0 \end{cases} \tag{3.4}$$

Notice that the conditions in (3.3) are causing a time-inconsistency problem in policy-making since they are not consistent with the conditions in (3.4). A simple way to solve this problem, at least theoretically, is to assume that the former conditions do not hold. This approach has been coined a 'timeless perspective' by Woodford (1999) since it assumes that the optimal policy has been implemented long time enough that agents in the economy believe that the central bank is committed to the policy.

Thus, when a commitment mechanism is not available in policy-making, the condition for optimal policy is

$$\pi_t=-\frac{\alpha\zeta}{\alpha\gamma-\delta}\cdot x_t+\frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}\cdot x_{t+1} \tag{3.5}$$

whereas when a commitment mechanism is available, the condition for optimal policy is

$$\begin{aligned}\pi_t \;=\; & -\frac{\delta}{\left(\alpha\gamma-\delta\right)\beta}\cdot\pi_{t-1}+\frac{\alpha\left(\beta+\delta\right)\zeta\left(1-\omega\right)}{\left(\alpha\gamma-\delta\right)\beta}\cdot x_{t-1}- \\ & \frac{\alpha\zeta}{\alpha\gamma-\delta}\cdot x_t+\frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}\cdot x_{t+1}\end{aligned} \tag{3.6}$$

Starting with the condition in (3.5), the lead output gap is included in the condition since the central bank partly can control the expected inflation rate, and this is because the lagged inflation rate is included in the expectations formation process. Notice that this term also vanish when $\omega=0$. Continuing with the condition in (3.6), terms for the lagged inflation rate and output gap are now added. The second term is typical in conditions when a commitment mechanism is available, whereas the first term is due to the presence of the cost channel. Notice that this term also vanish when $\delta=0$.

As already stated in the literature, there is no unique way in which a condition for optimal policy can be implemented by the central bank as an interest rate rule. Evans and Honkapohja (2003a) review different implementations of optimal policy in a new Keynesian model from the point of view of least squares learnability of a unique REE. Our aim is to examine optimal policy from the same perspective as them, but for a model with a cost channel and inflation rate expectations that partly are backward-looking. Thus, we derive expectations-based rules since they have nice properties in more typical new Keynesian models (see Evans and Honkapohja, 2003a–c, 2006).

The reason that expectations-based rules give rise to a REE that is stable under learning, as opposed to fundamentals-based rules, is that they are designed for this task. For the sake of the argument, assume that the economy is in the neighborhood of a REE, and that the central bank is using a fundamentals-based rule in policy-making. Unfortunately, since the rule is derived under the assumption that the economy is *in* a REE, there is no mechanism that forces agents to correct their beliefs regarding the economy's law of motion. The economy will, therefore, not converge to the REE since it is not stable under learning.

When it comes to expectations-based rules, they are also optimal policy rules, but do not assume that agents have rational expectations. Instead, when the central bank is using such a rule in policy-making, the interest rate is directly influenced by agents' private expectations that may not be rational, meaning that there is now a mechanism that is able to correct their beliefs regarding the economy's law of motion. In other words, the economy is forced to converge to the REE since it is stable under learning.

Thus, the key assumption when deriving expectations-based rules is to take agents' expectations as given and not imposing rational expectations, meaning that we have the following optimal interest rate rule

$$r_t = const. + \kappa_0 x_{t-1} + \kappa_1 x_t + \kappa_2 x^e_{t+1} + \kappa_3 \pi_{t-1} + \kappa_4 \pi^e_{t+1} \tag{3.7}$$

where e in the superscript denotes expectations that may not be rational. Under discretion in policy-making, the parameters in the rule are

$$\begin{cases} \kappa_0 = 0 & \kappa_3 = \frac{(\alpha\gamma+\beta)\omega}{\alpha\gamma-\delta} \\ \kappa_1 = \frac{\alpha\zeta}{(\alpha\gamma-\delta)^2} & \kappa_4 = \frac{(\alpha\gamma+\beta)(1-\omega)}{\alpha\gamma-\delta} \\ \kappa_2 = -\frac{1}{\alpha\gamma-\delta} \cdot \left(\frac{\alpha\beta(\beta+\delta)\zeta\omega}{\alpha\gamma-\delta} - \gamma\right) & \end{cases} \tag{3.8}$$

whereas under commitment, we have that

$$\begin{cases} \kappa_0 = -\frac{\alpha(\beta+\delta)\zeta(1-\omega)}{(\alpha\gamma-\delta)^2\beta} & \kappa_3 = \frac{1}{\alpha\gamma-\delta} \cdot \left((\alpha\gamma+\beta)\,\omega + \frac{\delta}{(\alpha\gamma-\delta)\beta}\right) \\ \kappa_1 = \frac{\alpha\zeta}{(\alpha\gamma-\delta)^2} & \kappa_4 = \frac{(\alpha\gamma+\beta)(1-\omega)}{\alpha\gamma-\delta} \\ \kappa_2 = -\frac{1}{\alpha\gamma-\delta} \cdot \left(\frac{\alpha\beta(\beta+\delta)\zeta\omega}{\alpha\gamma-\delta} - \gamma\right) & \end{cases} \tag{3.9}$$

The two differences between the rules are that a term for the lagged output gap is included when a commitment mechanism is available, and that the term for the lagged inflation rate is larger under commitment.

4 A determinate and E-stable REE?

The complete model in matrix form, both under discretion and commitment in policy-making, is[2]

$$\mathbf{\Gamma} \cdot \mathbf{y}_t = \mathbf{\Theta} \cdot \mathbf{y}^e_{t+1} + \mathbf{\Lambda} \cdot \mathbf{y}_{t-1} \tag{4.1}$$

where

$$\mathbf{\Gamma} = \begin{bmatrix} 1+\alpha\kappa_1 & 0 \\ -(\gamma+\delta\kappa_1) & 1 \end{bmatrix} \tag{4.2}$$

[2] We neglect from a constant in the expression since it does not affect our findings.

$$\mathbf{\Theta} = \begin{bmatrix} 1 - \alpha\kappa_2 & \alpha(1 - \omega - \kappa_4) \\ \delta\kappa_2 & \beta(1 - \omega) + \delta\kappa_4 \end{bmatrix} \tag{4.3}$$

$$\mathbf{\Lambda} = \begin{bmatrix} -\alpha\kappa_0 & \alpha(\omega - \kappa_3) \\ \delta\kappa_0 & \beta\omega + \delta\kappa_3 \end{bmatrix} \tag{4.4}$$

and

$$\mathbf{y}_t = \begin{bmatrix} x_t & \pi_t \end{bmatrix}' \tag{4.5}$$

Recall that $\kappa_0 = 0$ when there is discretion in policy-making.

To be able to determine whether the complete model has a determinate REE, a first step is to rewrite the model into first-order form, and, then, to compare the number of predetermined variables with the number of eigenvalues of a certain matrix that are outside the unit circle (see Blanchard and Kahn, 1980). Specifically, we make use of the following variable vector when rewriting the model in (4.1)–(4.5) and assuming discretion in policy-making

$$\mathbf{y}_{d,t} = \begin{bmatrix} x_t & \pi_t & \pi_t^L \equiv \pi_{t-1} \end{bmatrix}' \tag{4.6}$$

meaning that the relevant coefficient matrices are

$$\mathbf{\Gamma}_d = \begin{bmatrix} \mathbf{\Gamma} & & -\mathbf{\Lambda}_2 \\ 0 & 1 & 0 \end{bmatrix} \tag{4.7}$$

and

$$\mathbf{\Theta}_d = \begin{bmatrix} & & 0 \\ & \mathbf{\Theta} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4.8}$$

where $\mathbf{\Lambda}_2$ is the second column in matrix $\mathbf{\Lambda}$, because the complete model in matrix form is now

$$\mathbf{\Gamma}_d \cdot \mathbf{y}_{d,t} = \mathbf{\Theta}_d \cdot \mathbf{y}_{d,t+1}^e \tag{4.9}$$

Thus, since there is one variable in (4.6) that is predetermined, π_t^L, exactly one eigenvalue of the matrix $\mathbf{\Gamma}_d^{-1} \cdot \mathbf{\Theta}_d$ must be outside the unit circle to have a determinate REE. However, if more than one eigenvalue are outside the unit circle, we have an indeterminate REE, and if all eigenvalues are inside the unit circle, there is no stable REE.

To have a REE that is stable under learning, the parameter values in the agents' perceived law of motion of the economy have to converge to the economy's actual law of motion, and it is shown in McCallum (2007) that for a broad class of linear rational expectations models, which includes the model in this paper, a determinate solution is E-stable when the dating of expectations is time t. Consequently, since E-stability is closely related to least squares learning, all determinacy regions found below are also regions for least squares learnability of the unique REE (see Evans and Honkapohja, 2001, for an introduction to this learning literature).

However, deriving analytical conditions for determinacy is not meaningful since these expressions would be too large and cumbersome to interpret.

Therefore, we illustrate our findings numerically[3] using the following calibrated values of the structural parameters: $\alpha = \frac{1}{2}$ since it has been estimated to be $\frac{1}{2.04}$ and $\frac{1}{1.86}$ for the US economy (see Levin et al, 2005, and Lubik and Schorfheide, 2004, respectively); $\beta = 0.99$; $\gamma = 0.072$ since this is an estimate for the US economy under the assumption of unit intertemporal substitution elasticities in consumption and labor supply (see Chowdhury et al, 2006, for details); and $\delta = 0.03$ since this is an estimate for the US economy (see Chowdhury et al, 2006).

See Figure 1 for regions in the (ω, ζ)-space that give rise to a determinate and E-stable REE, an indeterminate REE and no stable REE.

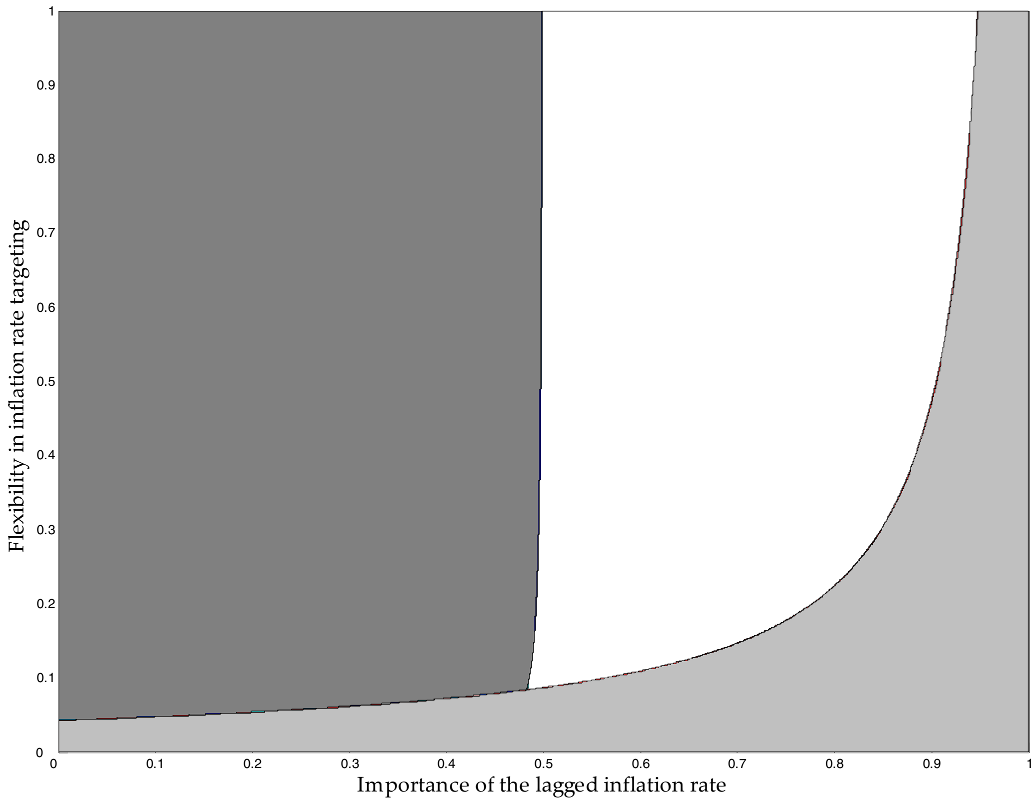

Figure 1. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

There is a determinate REE that is stable under learning when inflation rate targeting is not too flexible, except when the lagged inflation rate is very important in the expectations formation process. In this case, there is always a unique and learnable REE. Further on, since the welfare measure can be viewed as a second-order approximation of the representative household's utility function, there is an optimal degree of flexibility in inflation rate targeting. Woodford (2003) has looked into this matter in a model that is similar to the present model, and he found that almost strict inflation rate targeting to be optimal ($\zeta = 0.048$). This is also within the limit to have

[3] MATLAB routines for this purpose are available on request from the author.

a determinate REE that is stable under learning, except when the lagged inflation rate has almost no importance in inflation rate expectations.

If we decrease the size of the cost channel to $\delta = 0.015$, the region for a determinate REE that is stable under learning is much larger. The shape of the region in the (ω, ζ)-space is the same as when $\delta = 0.03$, but inflation rate targeting can be much more flexible. See Figure 2 for this case.

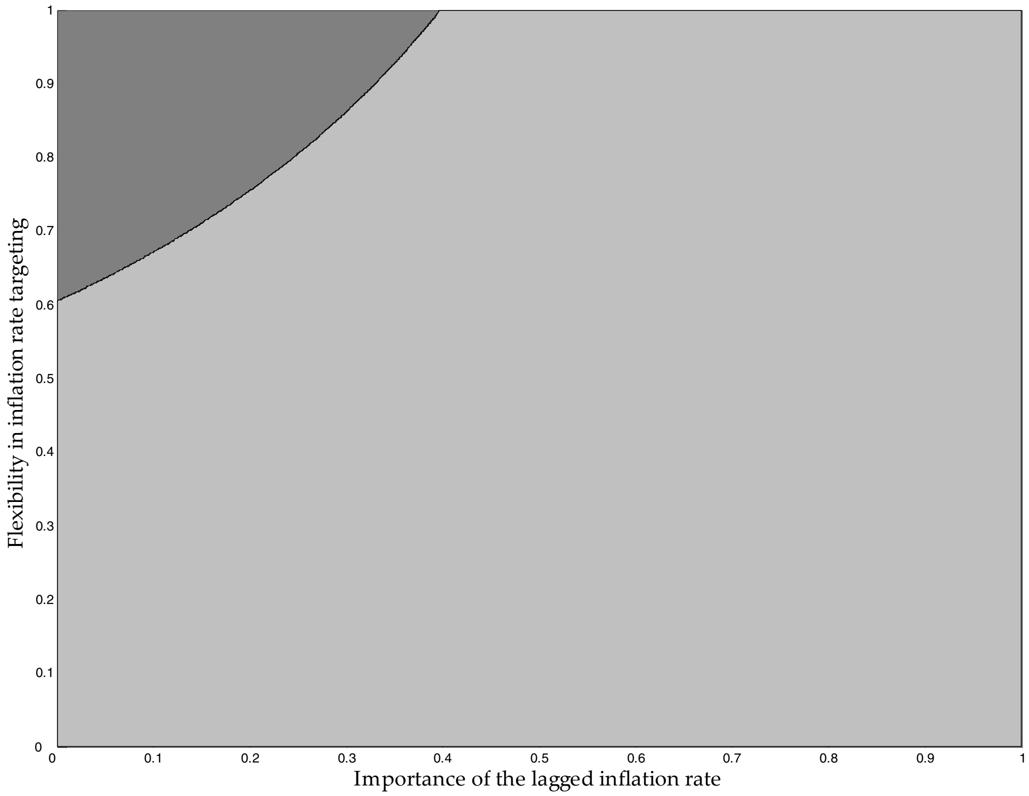

Figure 2. Region for a determinate REE that is stable under learning (see light area) and region for an indeterminate REE (see dark area)

In fact, when there is no cost channel in the model, there are no restrictions in the (ω, ζ)-space[4] to have a determinate and E-stable REE. We already know that this is true when backward-looking expectations have no role in inflation rate expectations (see Evans and Honkapohja, 2003b), but it is now clear that this result also holds irrespective of the importance of the lagged inflation rate in the expectations formation process.

However, if the size of the cost channel is twice as large as in the baseline case, $\delta = 0.06$, the behavior of the economy is dramatically different. In this case, there is no longer any region in the (ω, ζ)-space for a determinate REE that is stable under learning. Instead, if we restrict our attention to almost strict inflation rate targeting, there is a multiplicity of stable REE, whereas a more flexible targeting in combination with a large weight given to the lagged inflation rate in the expectations formation process, there is no stable REE at all. See Figure 3 for this case.

[4] Recall that $\zeta \in [0, 1]$. Thus, when $\zeta = 1$, the central bank puts equal weights on the inflation rate and the output gap when maximizing welfare.

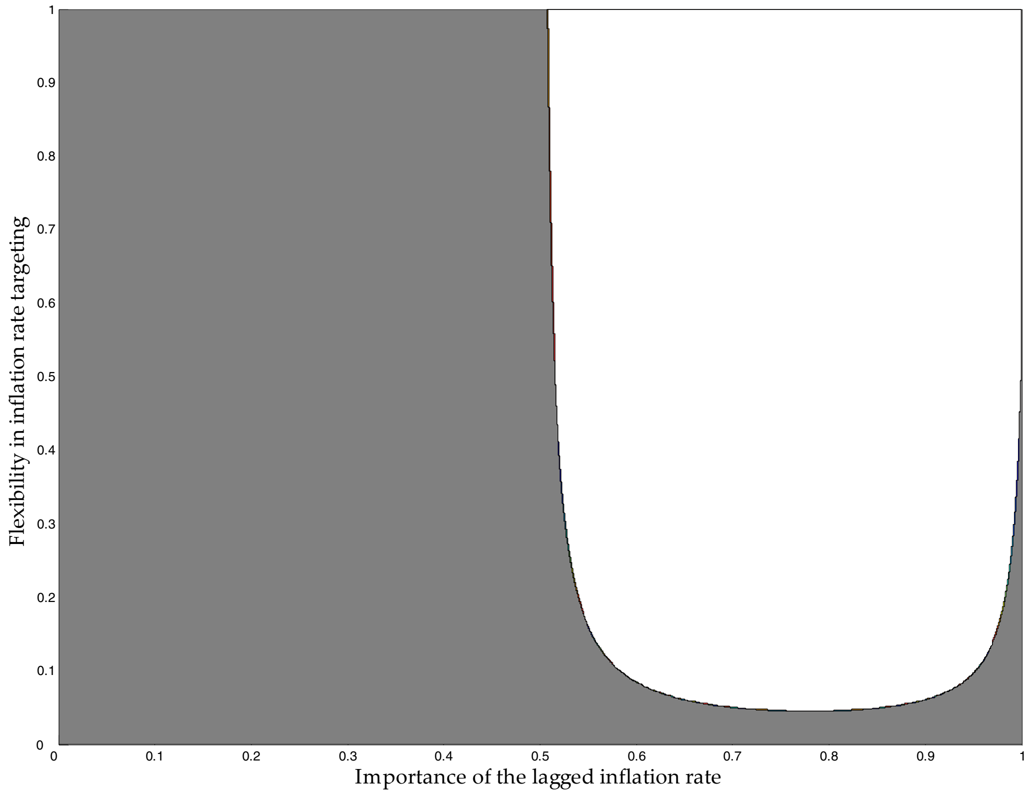

Figure 3. Regions for an indeterminate REE (see dark area) and no stable REE (see white area)

The reason for this finding is that a large cost channel has a perverse effect on the parameters in the optimal policy rule. Specifically, when

$$\delta > \alpha\gamma \tag{4.10}$$

the central bank will decrease the interest rate when the lagged and expected inflation rates increase, meaning that monetary policy is stimulating the economy. It is clear that in the absence of a cost channel, this perverse situation can never arise, whereas it is more likely to happen when the cost channel is larger.

Under commitment in policy-making, we make use of the following variable vector when rewriting the model in (4.1)–(4.5)

$$\mathbf{y}_{c,t} = \begin{bmatrix} x_t & \pi_t & x_t^L \equiv x_{t-1} & \pi_t^L \equiv \pi_{t-1} \end{bmatrix}' \tag{4.11}$$

meaning that the relevant coefficient matrices are

$$\mathbf{\Gamma}_c = \begin{bmatrix} \multicolumn{2}{c}{\mathbf{\Gamma}} & -\mathbf{\Lambda}_1 & -\mathbf{\Lambda}_2 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{4.12}$$

and

$$\mathbf{\Theta}_c = \begin{bmatrix} & & 0 & 0 \\ & \mathbf{\Theta} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.13}$$

where $\mathbf{\Lambda}_1$ and $\mathbf{\Lambda}_2$ are the first and second columns in matrix $\mathbf{\Lambda}$, respectively, because the complete model in matrix form is now

$$\mathbf{\Gamma}_c \cdot \mathbf{y}_{c,t} = \mathbf{\Theta}_c \cdot \mathbf{y}^e_{c,t+1} \tag{4.14}$$

Thus, since there are two variables in (4.11) that are predetermined, x^L_t and π^L_t, exactly two eigenvalues of the matrix $\mathbf{\Gamma}_c^{-1} \cdot \mathbf{\Theta}_c$ must be outside the unit circle to have a determinate REE. However, if more than two eigenvalues are outside the unit circle, we have an indeterminate REE, and if less than two eigenvalues are outside the unit circle, there is no stable REE.

Turning to our findings, there are no restrictions in the (ω, ζ)-space to have a determinate REE that is stable under learning, and this result holds for the same sizes of the cost channel as we examined above when there was no commitment mechanism in policy-making (i.e., $\delta = 0$, $\delta = 0.015$, $\delta = 0.03$ and $\delta = 0.06$). In fact, after investigating several parameter settings, including unrealistic settings, our conjecture is that we always have a unique and least squares learnable REE.

5 Misapprehensions in policy-making

What happens if the central bank is unaware of the cost channel for monetary disturbances, and, therefore, believe that $\delta = 0$ in the interest rate rule? Moreover, what happens if the central bank neglects the fact that inflation rate expectations partly are backward-looking, and, therefore, believe that $\omega = 0$ in the interest rate rule?

Starting with the belief that $\delta = 0$ when, in fact, $\delta = 0.03$, the shape of the region in the (ω, ζ)-space for a determinate and E-stable REE is unaffected when there is discretion in policy-making, but inflation rate targeting can now be more flexible.[5] It might, therefore, be tempting to believe that the central bank should not care about the cost channel when setting the interest rate. However, one must not forget that monetary policy no longer is optimal due to the misapprehension of the size of the cost channel. When it comes to commitment in policy-making, there are no restrictions in the (ω, ζ)-space to have a determinate REE that is stable under learning.

Continuing with the belief that $\omega = 0$ when, in fact, $\omega > 0$, the maximum flexibility in inflation rate targeting is unaffected by the importance of the lagged inflation rate to have a determinate and E-stable REE when there is discretion in policy-making, and the region in the (ω, ζ)-space for a determinate and E-stable REE is now smaller. When it comes to commitment

[5] To save space, we do not show any figures in this section. However, in the Appendix, we show lots of figures for different combinations of misapprehensions in policy-making and sizes of the cost channel, both under discretion and commitment.

in policy-making, there are almost no restrictions in the (ω, ζ)-space to have a determinate REE that is stable under learning.

6 Conclusion

In recent years, there has been an increased interest for the cost channel for monetary disturbances, which also is true for a hybrid specification of the new Keynesian Phillips curve. What we have done in this paper is to show that expectations-based rules, originally proposed by Evans and Honkapohja (2003a)–(2006), still have desirable properties in a new Keynesian model with the aforementioned features. In fact, under commitment in policy-making, it seems to be the case that there are no restrictions in the (ω, ζ)-space to have a determinate REE that is stable under learning, whereas under discretion, inflation rate targeting cannot be too flexible.

Thus, if we summarize our findings in one sentence: it is not only the case that optimal policy under commitment is superior to a discretionary policy from a welfare perspective, there is also no guarantee that the latter policy will secure an REE that is unique and least squares learnable, which is the case when there is commitment in policy-making.

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Technical Appendix

Constraint in the Lagrangian

Substitute the expected inflation rate in (2.2) into the IS and AS curves in (2.1)

$$\begin{cases} x_t = E_t\left[x_{t+1}\right] - \alpha\left(r_t - \left(\omega\pi_{t-1} + (1-\omega)\,E_t\left[\pi_{t+1}\right]\right)\right) \\ \pi_t = \beta\left(\omega\pi_{t-1} + (1-\omega)\,E_t\left[\pi_{t+1}\right]\right) + \gamma x_t + \delta r_t + \varepsilon_t \end{cases}$$

or

$$\begin{cases} x_t = E_t\left[x_{t+1}\right] - \alpha r_t + \alpha\omega\pi_{t-1} + \alpha\,(1-\omega)\,E_t\left[\pi_{t+1}\right] \\ \pi_t = \beta\omega\pi_{t-1} + \beta\,(1-\omega)\,E_t\left[\pi_{t+1}\right] + \gamma x_t + \delta r_t + \varepsilon_t \end{cases} \tag{A.1}$$

Solve the first equation for r_t, and substitute this equation into the second equation in (A.1)

$$\begin{cases} r_t = \frac{1}{\alpha}\cdot E_t\left[x_{t+1}\right] + \omega\pi_{t-1} + (1-\omega)\,E_t\left[\pi_{t+1}\right] - \frac{1}{\alpha}\cdot x_t \\ \pi_t = \beta\omega\pi_{t-1} + \beta\,(1-\omega)\,E_t\left[\pi_{t+1}\right] + \gamma x_t + \delta r_t + \varepsilon_t \end{cases}$$

$$\begin{aligned} \pi_t \;&=\; \beta\omega\pi_{t-1} + \beta\,(1-\omega)\,E_t\left[\pi_{t+1}\right] + \gamma x_t + \\ &\quad\; \delta\cdot\left(\frac{1}{\alpha}\cdot E_t\left[x_{t+1}\right] + \omega\pi_{t-1} + (1-\omega)\,E_t\left[\pi_{t+1}\right] - \frac{1}{\alpha}\cdot x_t\right) + \varepsilon_t \end{aligned}$$

or

$$\begin{aligned} \pi_t \;&=\; (\beta+\delta)\,\omega\pi_{t-1} + (\beta+\delta)\,(1-\omega)\,E_t\left[\pi_{t+1}\right] - \\ &\quad\; \left(\frac{\delta}{\alpha} - \gamma\right)\cdot x_t + \frac{\delta}{\alpha}\cdot E_t\left[x_{t+1}\right] + \varepsilon_t \end{aligned}$$

First-order condition when discretion in policy-making

Solve the first equation in (3.3) for λ_t

$$\lambda_t = -\frac{2\alpha\zeta}{\alpha\gamma - \delta}\cdot x_t$$

Forward this equation one time period

$$\lambda_{t+1} = -\frac{2\alpha\zeta}{\alpha\gamma - \delta}\cdot x_{t+1}$$

Substitute the equations for λ_t and λ_{t+1} into the second equation in (3.3)

$$2\pi_t - \left(-\frac{2\alpha\zeta}{\alpha\gamma - \delta}\cdot x_t\right) + \beta\,(\beta+\delta)\,\omega\cdot\left(-\frac{2\alpha\zeta}{\alpha\gamma - \delta}\cdot x_{t+1}\right) = 0$$

or

$$\pi_t = -\frac{\alpha\zeta}{\alpha\gamma - \delta}\cdot x_t + \frac{\alpha\beta\,(\beta+\delta)\,\zeta\omega}{\alpha\gamma - \delta}\cdot x_{t+1} \tag{3.5}$$

First-order condition when commitment in policy-making

Solve the first equation in (3.4) for λ_t

$$\lambda_t = -\frac{\delta}{(\alpha\gamma - \delta)\beta} \cdot \lambda_{t-1} - \frac{2\alpha\zeta}{\alpha\gamma - \delta} \cdot x_t \tag{A.2}$$

Forward this equation one time period

$$\lambda_{t+1} = -\frac{\delta}{(\alpha\gamma - \delta)\beta} \cdot \lambda_t - \frac{2\alpha\zeta}{\alpha\gamma - \delta} \cdot x_{t+1}$$

Substitute this equation into the second equation in (3.4)

$$\begin{aligned} & (\beta + \delta)(1 - \omega)\lambda_{t-1} + 2\beta\pi_t - \beta\lambda_t + \\ & \beta^2 (\beta + \delta)\omega \cdot \left(-\frac{\delta}{(\alpha\gamma - \delta)\beta} \cdot \lambda_t - \frac{2\alpha\zeta}{\alpha\gamma - \delta} \cdot x_{t+1} \right) \\ = \; & 0 \end{aligned}$$

or

$$\begin{aligned} & (\beta + \delta)(1 - \omega)\lambda_{t-1} + 2\beta\pi_t - \\ & \beta \left(1 + \frac{(\beta + \delta)\delta\omega}{\alpha\gamma - \delta} \right) \cdot \lambda_t - \frac{2\alpha\beta^2 (\beta + \delta)\zeta\omega}{\alpha\gamma - \delta} \cdot x_{t+1} \\ = \; & 0 \end{aligned}$$

or

$$\begin{aligned} \lambda_t \; = \; & \frac{(\alpha\gamma - \delta)(\beta + \delta)(1 - \omega)}{(\alpha\gamma + (\beta + \delta)\delta\omega - \delta)\beta} \cdot \lambda_{t-1} - \\ & \frac{2\alpha\beta(\beta + \delta)\zeta\omega}{\alpha\gamma + (\beta + \delta)\delta\omega - \delta} \cdot x_{t+1} + \frac{2(\alpha\gamma - \delta)}{\alpha\gamma + (\beta + \delta)\delta\omega - \delta} \cdot \pi_t \end{aligned} \tag{A.3}$$

(A.2) and (A.3) are two equations in λ_t and λ_{t-1}. Solve these equations for these variables, *but be aware that λ_t is λ_{t-1} one time period forward in time*

$$\begin{cases} \lambda_t = -A\lambda_{t-1} - Bx_t \\ \lambda_t = C\lambda_{t-1} - Dx_{t+1} + E\pi_t \end{cases} \tag{A.4}$$

or

$$-A\lambda_{t-1} - Bx_t = C\lambda_{t-1} - Dx_{t+1} + E\pi_t$$

or

$$\lambda_{t-1} = -\frac{B}{A + C} \cdot x_t + \frac{D}{A + C} \cdot x_{t+1} - \frac{E}{A + C} \cdot \pi_t$$

Forward this equation one time period

$$\lambda_t = -\frac{B}{A + C} \cdot x_{t+1} + \frac{D}{A + C} \cdot x_{t+2} - \frac{E}{A + C} \cdot \pi_{t+1}$$

Substitute the equations for λ_{t-1} and λ_t into the first equation in (A.4)

$$\begin{aligned} & -\frac{B}{A+C}\cdot x_{t+1}+\frac{D}{A+C}\cdot x_{t+2}-\frac{E}{A+C}\cdot \pi_{t+1} \\ = & \frac{AB}{A+C}\cdot x_t-\frac{AD}{A+C}\cdot x_{t+1}+\frac{AE}{A+C}\cdot \pi_t - Bx_t \end{aligned}$$

or

$$\pi_{t+1}=-A\pi_t+\frac{BC}{E}\cdot x_t+\frac{AD-B}{E}\cdot x_{t+1}+\frac{D}{E}\cdot x_{t+2}$$

Backward this equation one time period

$$\pi_t=-A\pi_{t-1}+\frac{BC}{E}\cdot x_{t-1}+\frac{AD-B}{E}\cdot x_t+\frac{D}{E}\cdot x_{t+1}$$

and substitute back A, B, C and D into this equation

$$\begin{aligned} \pi_t = & -\frac{\delta}{(\alpha\gamma-\delta)\beta}\cdot\pi_{t-1}+ \\ & \frac{2\alpha\zeta}{\alpha\gamma-\delta}\cdot\frac{(\alpha\gamma-\delta)(\beta+\delta)(1-\omega)}{(\alpha\gamma+(\beta+\delta)\delta\omega-\delta)\beta}\cdot\frac{\alpha\gamma+(\beta+\delta)\delta\omega-\delta}{2(\alpha\gamma-\delta)}\cdot x_{t-1}+ \\ & \left(\frac{\delta}{(\alpha\gamma-\delta)\beta}\cdot\frac{2\alpha\beta(\beta+\delta)\zeta\omega}{\alpha\gamma+(\beta+\delta)\delta\omega-\delta}-\frac{2\alpha\zeta}{\alpha\gamma-\delta}\right)\cdot \\ & \frac{\alpha\gamma+(\beta+\delta)\delta\omega-\delta}{2(\alpha\gamma-\delta)}\cdot x_t+ \\ & \frac{2\alpha\beta(\beta+\delta)\zeta\omega}{\alpha\gamma+(\beta+\delta)\delta\omega-\delta}\cdot\frac{\alpha\gamma+(\beta+\delta)\delta\omega-\delta}{2(\alpha\gamma-\delta)}\cdot x_{t+1} \end{aligned}$$

or

$$\begin{aligned} \pi_t = & -\frac{\delta}{(\alpha\gamma-\delta)\beta}\cdot\pi_{t-1}+\frac{\alpha(\beta+\delta)\zeta(1-\omega)}{(\alpha\gamma-\delta)\beta}\cdot x_{t-1}- \\ & \frac{\alpha\zeta}{\alpha\gamma-\delta}\cdot x_t+\frac{\alpha\beta(\beta+\delta)\zeta\omega}{\alpha\gamma-\delta}\cdot x_{t+1} \end{aligned} \tag{3.6}$$

Derive the interest rate rule when discretion in policy-making without imposing rational expectations

Substitute the first equation in (A.1) into the second equation in (A.1), but do not assume rational expectations

$$\begin{aligned} \pi_t = & \beta\omega\pi_{t-1}+\beta(1-\omega)\pi^e_{t+1}+ \\ & \gamma\left(x^e_{t+1}-\alpha r_t+\alpha\omega\pi_{t-1}+\alpha(1-\omega)\pi^e_{t+1}\right)+\delta r_t+\varepsilon_t \end{aligned}$$

or

$$\begin{aligned} \pi_t = & (\alpha\gamma+\beta)\omega\pi_{t-1}+(\alpha\gamma+\beta)(1-\omega)\pi^e_{t+1}+ \\ & \gamma x^e_{t+1}-(\alpha\gamma-\delta)r_t+\varepsilon_t \end{aligned} \tag{A.5}$$

Substitute the first-order condition in (3.5) into (A.5)

$$\begin{aligned}
& -\frac{\alpha\zeta}{\alpha\gamma-\delta}\cdot x_t + \frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}\cdot x^e_{t+1} \\
= & \left(\alpha\gamma+\beta\right)\omega\pi_{t-1} + \left(\alpha\gamma+\beta\right)\left(1-\omega\right)\pi^e_{t+1} + \\
& \gamma x^e_{t+1} - \left(\alpha\gamma-\delta\right) r_t + \varepsilon_t
\end{aligned}$$

or

$$\begin{aligned}
r_t = & \frac{\alpha\zeta}{\left(\alpha\gamma-\delta\right)^2}\cdot x_t - \frac{1}{\alpha\gamma-\delta}\cdot\left(\frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}-\gamma\right)\cdot x^e_{t+1} + \\
& \frac{\left(\alpha\gamma+\beta\right)\omega}{\alpha\gamma-\delta}\cdot\pi_{t-1} + \frac{\left(\alpha\gamma+\beta\right)\left(1-\omega\right)}{\alpha\gamma-\delta}\cdot\pi^e_{t+1} + \\
& \frac{1}{\alpha\gamma-\delta}\cdot\varepsilon_t
\end{aligned}$$

or

$$r_t = const. + \kappa_0 x_{t-1} + \kappa_1 x_t + \kappa_2 x^e_{t+1} + \kappa_3\pi_{t-1} + \kappa_4\pi^e_{t+1} \tag{3.7}$$

Derive the interest rate rule when commitment in policy-making without imposing rational expectations

Substitute the first-order condition in (3.6) into (A.5)

$$\begin{aligned}
& -\frac{\delta}{\left(\alpha\gamma-\delta\right)\beta}\cdot\pi_{t-1} + \frac{\alpha\left(\beta+\delta\right)\zeta\left(1-\omega\right)}{\left(\alpha\gamma-\delta\right)\beta}\cdot x_{t-1} - \\
& \frac{\alpha\zeta}{\alpha\gamma-\delta}\cdot x_t + \frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}\cdot x^e_{t+1} \\
= & \left(\alpha\gamma+\beta\right)\omega\pi_{t-1} + \left(\alpha\gamma+\beta\right)\left(1-\omega\right)\pi^e_{t+1} + \\
& \gamma x^e_{t+1} - \left(\alpha\gamma-\delta\right) r_t + \varepsilon_t
\end{aligned}$$

or

$$\begin{aligned}
r_t = & -\frac{\alpha\left(\beta+\delta\right)\zeta\left(1-\omega\right)}{\left(\alpha\gamma-\delta\right)^2\beta}\cdot x_{t-1} + \frac{\alpha\zeta}{\left(\alpha\gamma-\delta\right)^2}\cdot x_t - \\
& \frac{1}{\alpha\gamma-\delta}\cdot\left(\frac{\alpha\beta\left(\beta+\delta\right)\zeta\omega}{\alpha\gamma-\delta}-\gamma\right)\cdot x^e_{t+1} + \\
& \frac{1}{\alpha\gamma-\delta}\cdot\left(\left(\alpha\gamma+\beta\right)\omega + \frac{\delta}{\left(\alpha\gamma-\delta\right)\beta}\right)\cdot\pi_{t-1} + \\
& \frac{\left(\alpha\gamma+\beta\right)\left(1-\omega\right)}{\alpha\gamma-\delta}\cdot\pi^e_{t+1} + \frac{1}{\alpha\gamma-\delta}\cdot\varepsilon_t
\end{aligned}$$

or (3.7).

Complete model under both discretion and commitment in policy-making

Substitute the interest rate rule in (3.7) into the equations in (A.1), do not assume rational expectations, and neglect from constants

$$\begin{cases}
x_t = x^e_{t+1} - \alpha\left(\kappa_0 x_{t-1} + \kappa_1 x_t + \kappa_2 x^e_{t+1} + \kappa_3\pi_{t-1} + \kappa_4\pi^e_{t+1}\right) + \\
\qquad \alpha\omega\pi_{t-1} + \alpha\left(1-\omega\right)\pi^e_{t+1} \\
\pi_t = \beta\omega\pi_{t-1} + \beta\left(1-\omega\right)\pi^e_{t+1} + \gamma x_t + \\
\qquad \delta\left(\kappa_0 x_{t-1} + \kappa_1 x_t + \kappa_2 x^e_{t+1} + \kappa_3\pi_{t-1} + \kappa_4\pi^e_{t+1}\right)
\end{cases}$$

or

$$\left\{\begin{array}{c}(1+\alpha\kappa_1)\,x_t=(1-\alpha\kappa_2)\,x^e_{t+1}+\alpha\,(1-\omega-\kappa_4)\,\pi^e_{t+1}-\\ \alpha\kappa_0 x_{t-1}+\alpha\,(\omega-\kappa_3)\,\pi_{t-1}\\ -(\gamma+\delta\kappa_1)\,x_t+\pi_t=\delta\kappa_2 x^e_{t+1}+(\beta\,(1-\omega)+\delta\kappa_4)\,\pi^e_{t+1}+\\ \delta\kappa_0 x_{t-1}+(\beta\omega+\delta\kappa_3)\,\pi_{t-1}\end{array}\right.$$

or (4.1)–(4.5).

Appendix

Figure	Type of optimal policy	Size of cost channel	Aware of the cost channel?	Aware of lagged inflation rate?
1	Discretion	Normal	Yes	Yes
A.1	Discretion	Normal	No	Yes
A.2	Discretion	Normal	Yes	No
A.3	Discretion	Normal	No	No
2	Discretion	Small	Yes	Yes
No figure[1]	Discretion	Small	No	Yes
A.4	Discretion	Small	Yes	No
No figure	Discretion	Small	No	No
3	Discretion	Large	Yes	Yes
A.5	Discretion	Large	No	Yes
A.6	Discretion	Large	Yes	No
A.7	Discretion	Large	No	No
No figure	Discretion	No channel	-	Yes
No figure	Discretion	No channel	-	No
No figure	Commitment	Normal	Yes	Yes
No figure	Commitment	Normal	No	Yes
A.8	Commitment	Normal	Yes	No
A.9	Commitment	Normal	No	No
No figure	Commitment	Small	Yes	Yes
No figure	Commitment	Small	No	Yes
A.10	Commitment	Small	Yes	No
No figure	Commitment	Small	No	No
No figure	Commitment	Large	Yes	Yes
A.11	Commitment	Large	No	Yes
A.12	Commitment	Large	Yes	No
A.13	Commitment	Large	No	No
No figure	Commitment	No channel	-	Yes
No figure	Commitment	No channel	-	No

[1] When there is always a determinate REE that is stable under learning, we do not show any figure.

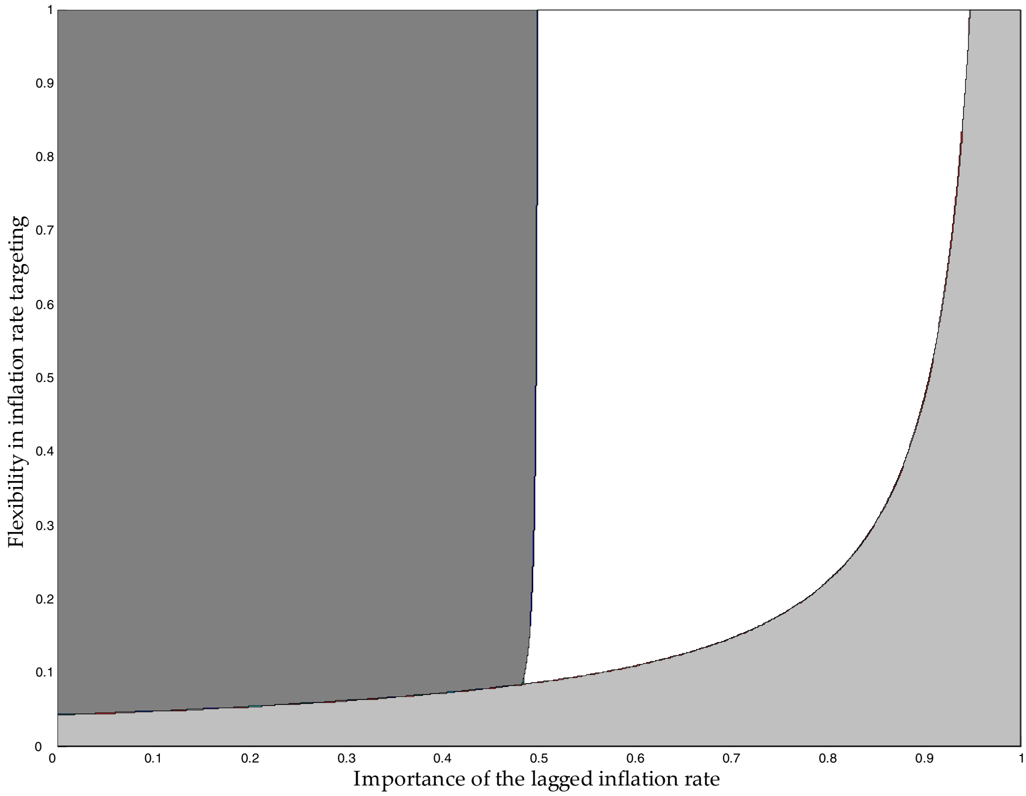

Figure 1. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

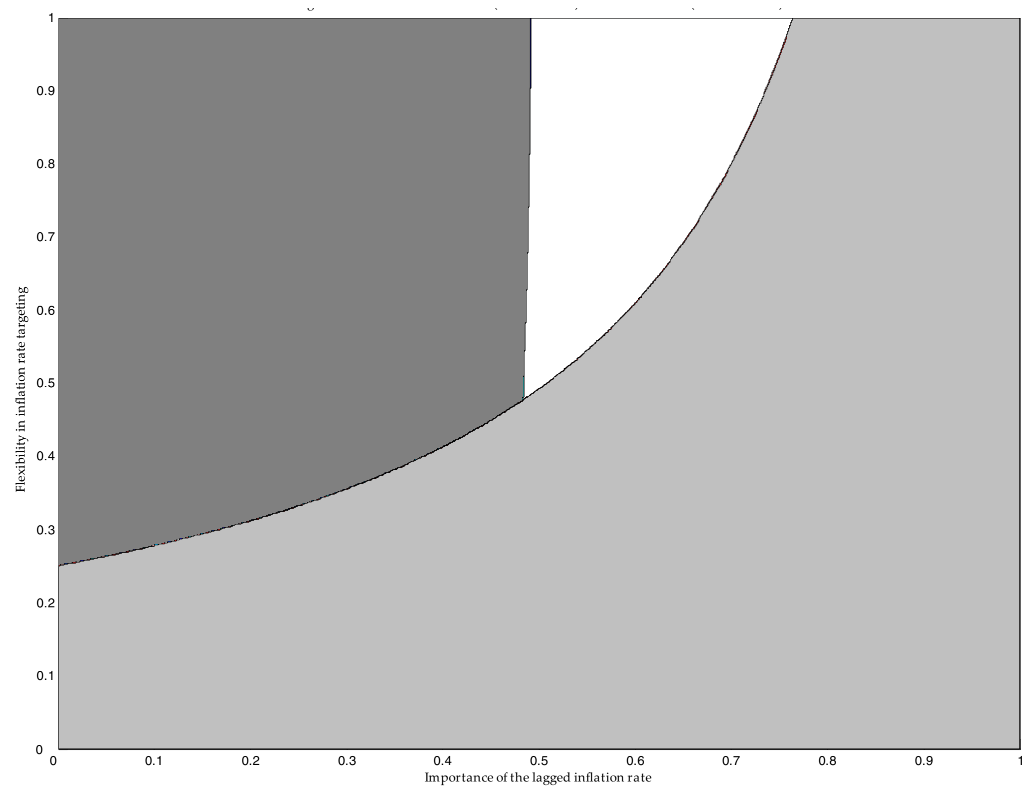

Figure A.1. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

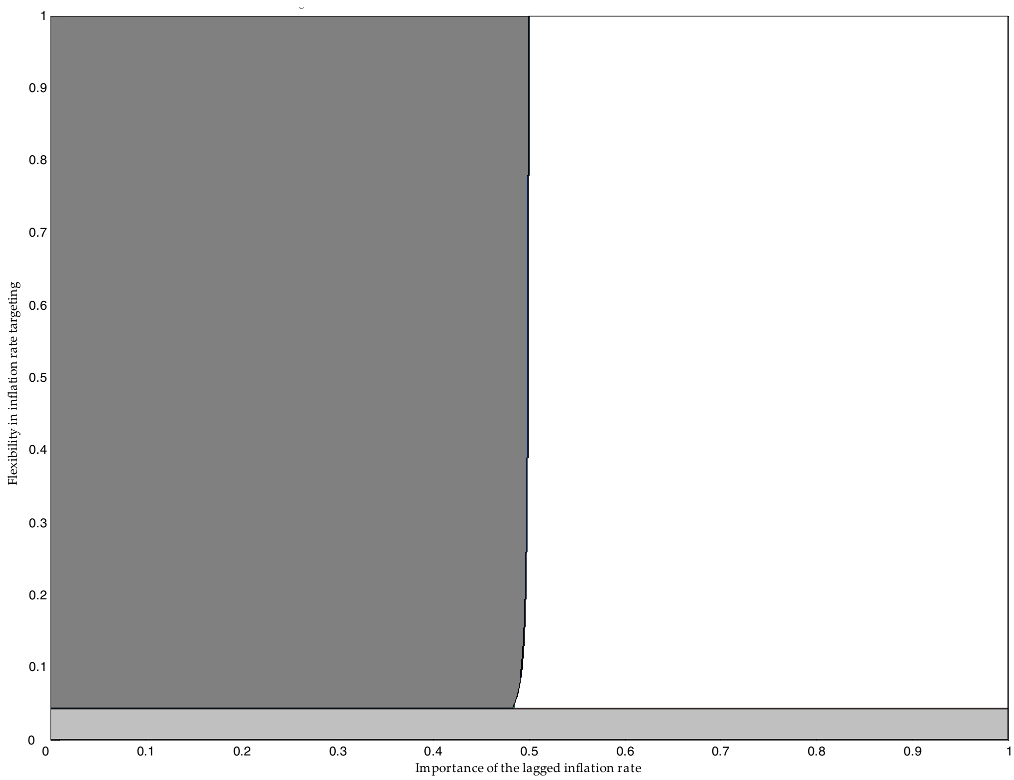

Figure A.2. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

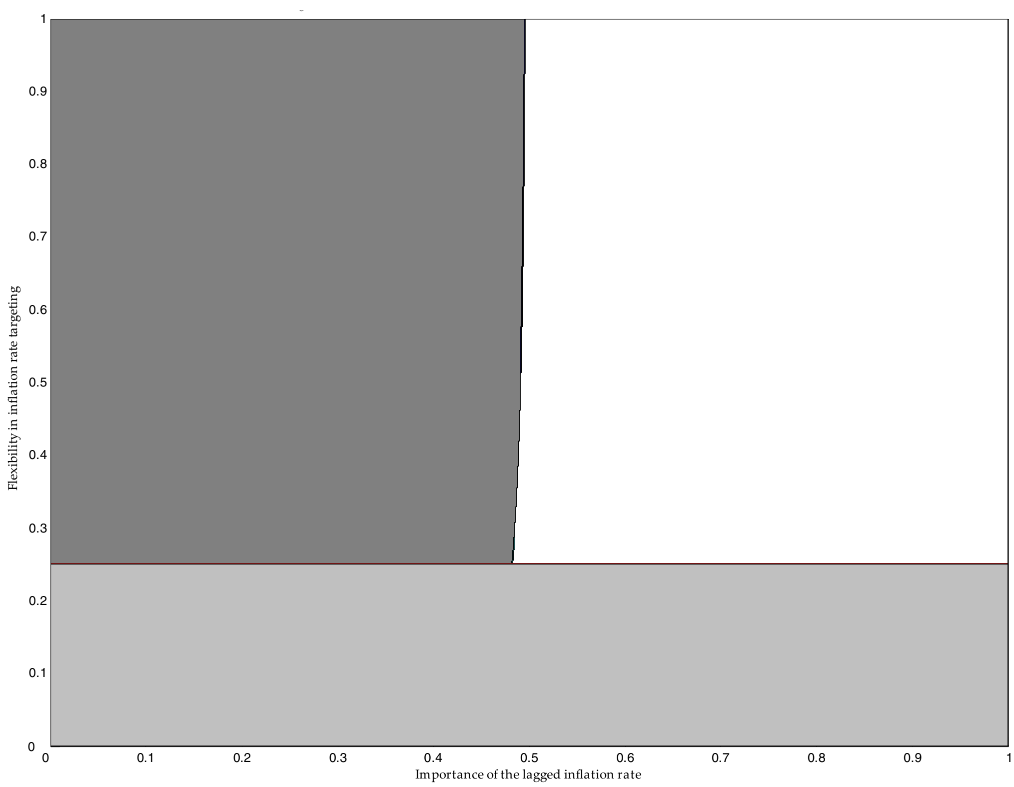

Figure A.3. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

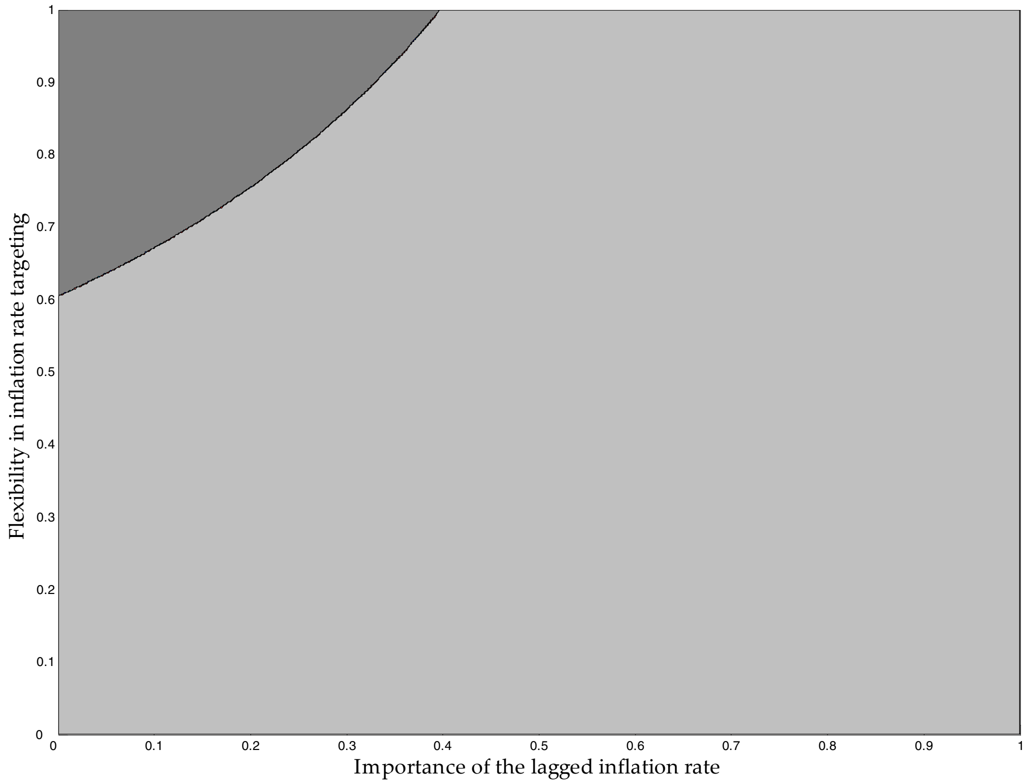

Figure 2. Region for a determinate REE that is stable under learning (see light area) and region for an indeterminate REE (see dark area)

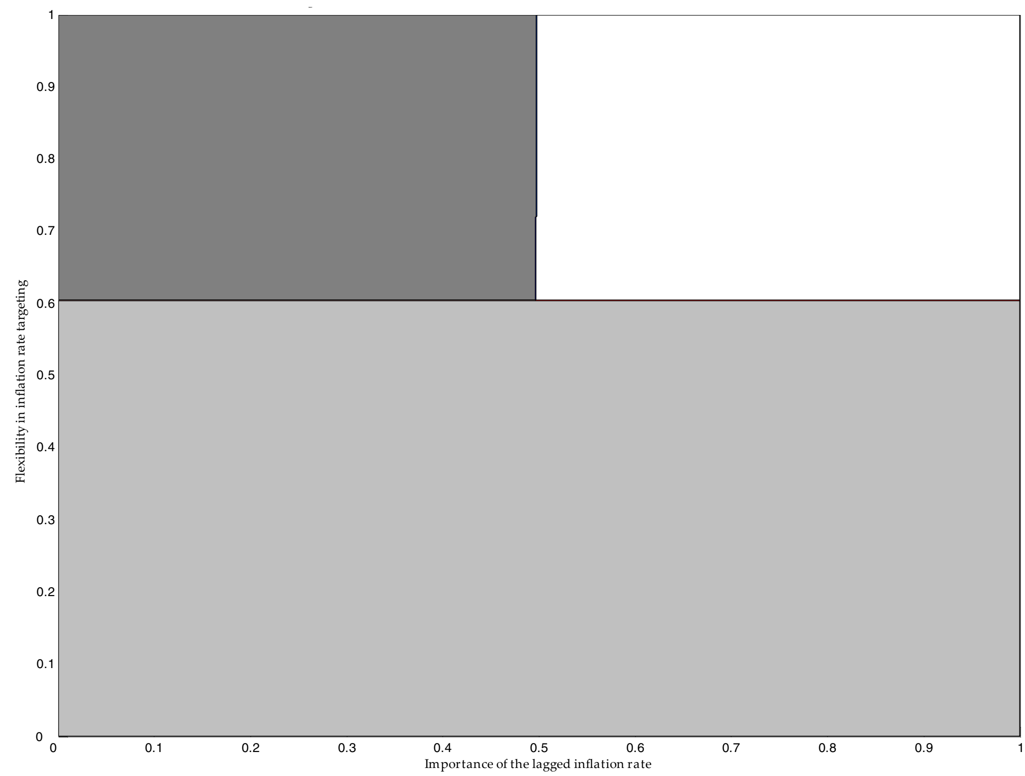

Figure A.4. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

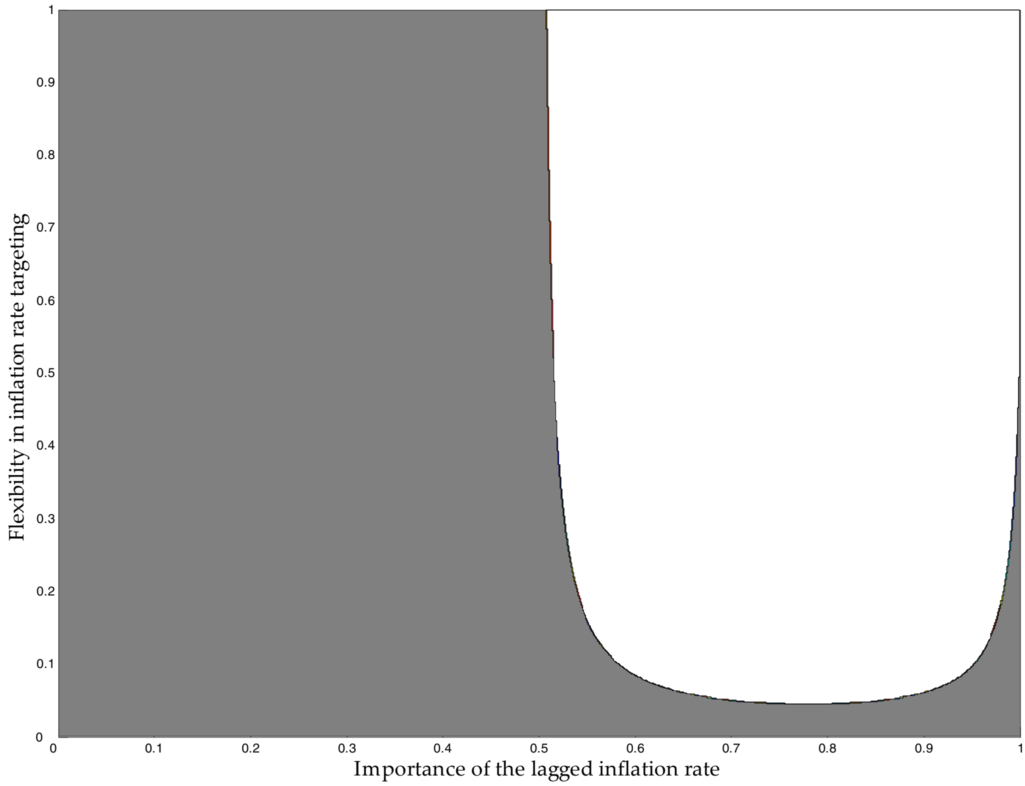

Figure 3. Regions for an indeterminate REE (see dark area) and no stable REE (see white area)

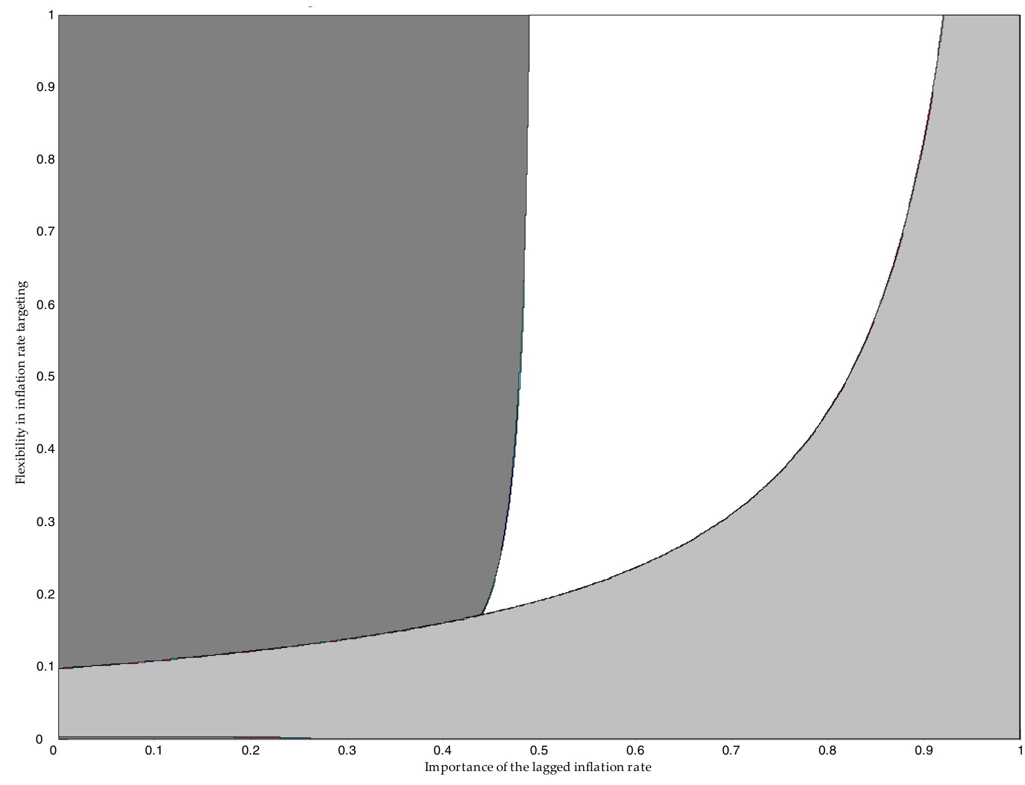

Figure A.5. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

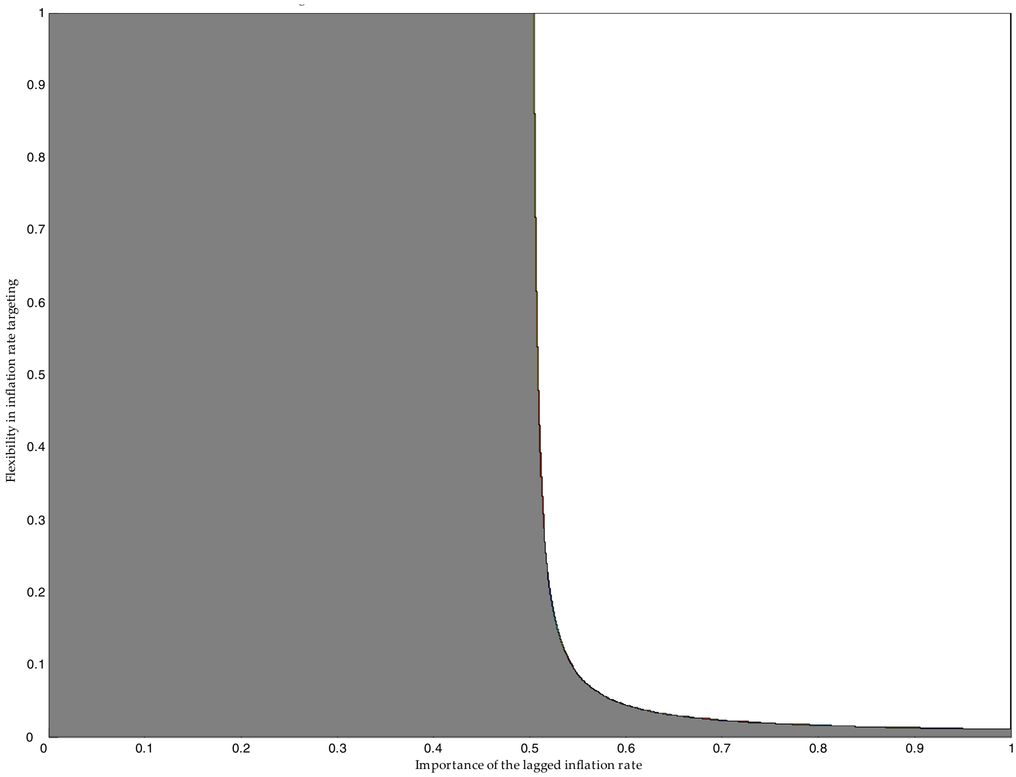

Figure A.6. Regions for an indeterminate REE (see dark area) and no stable REE (see white area)

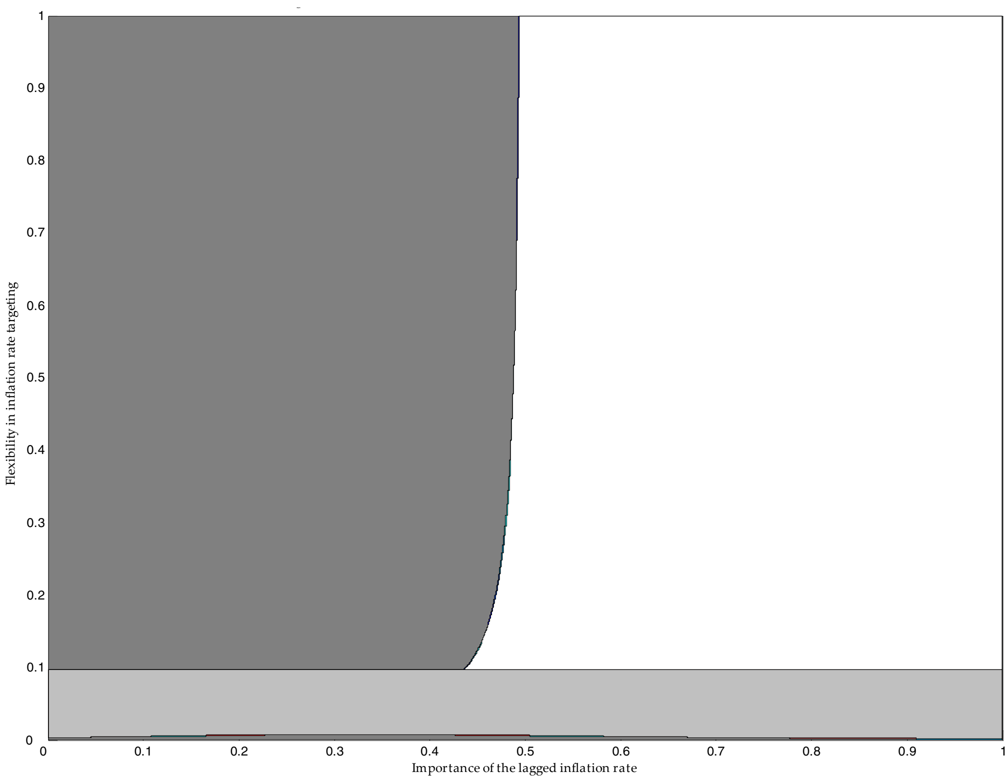

Figure A.7. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

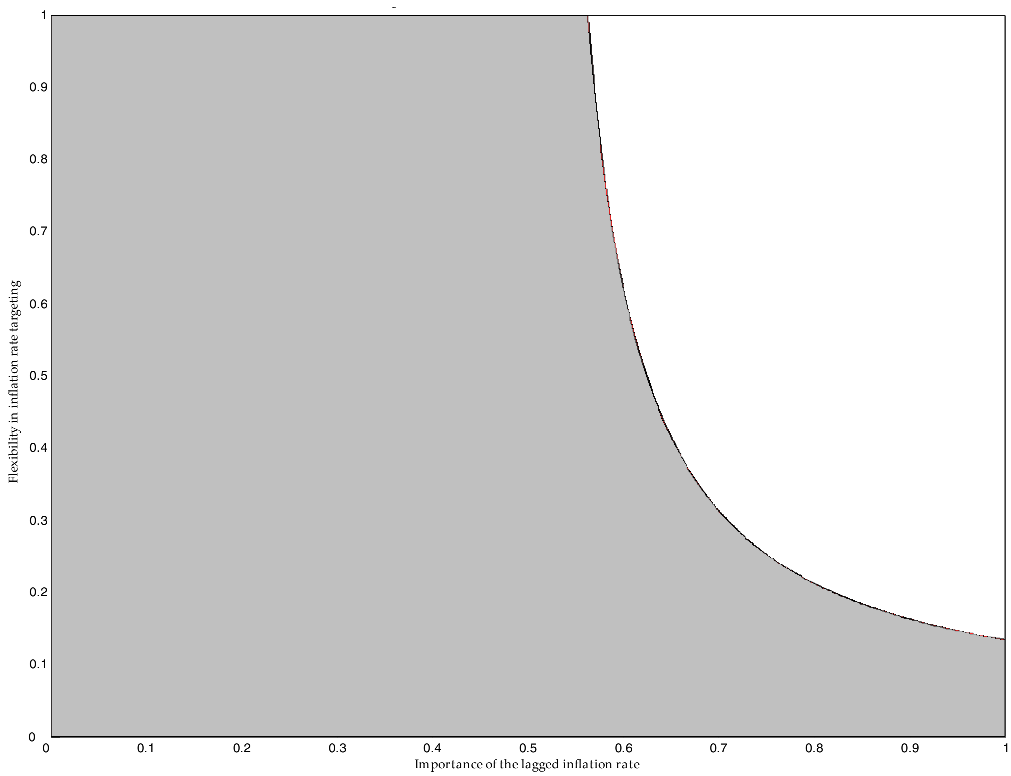

Figure A.8. Region for a determinate REE that is stable under learning (see light area) and region when there is no stable REE (see white area)

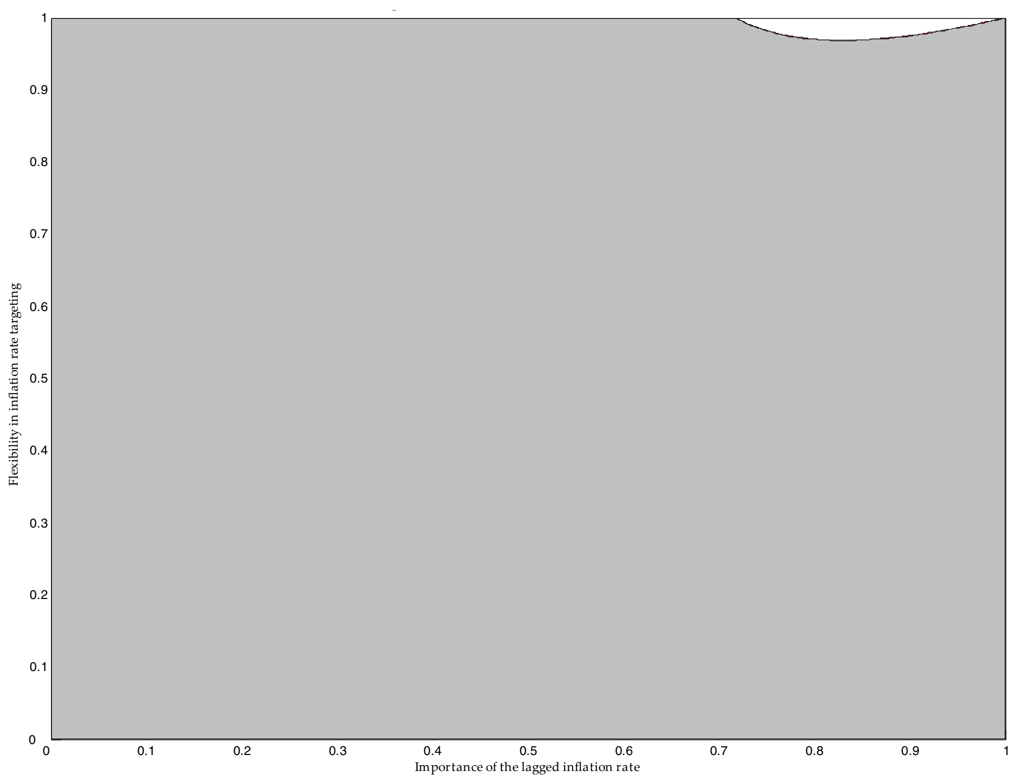

Figure A.9. Region for a determinate REE that is stable under learning (see light area) and region when there is no stable REE (see white area)

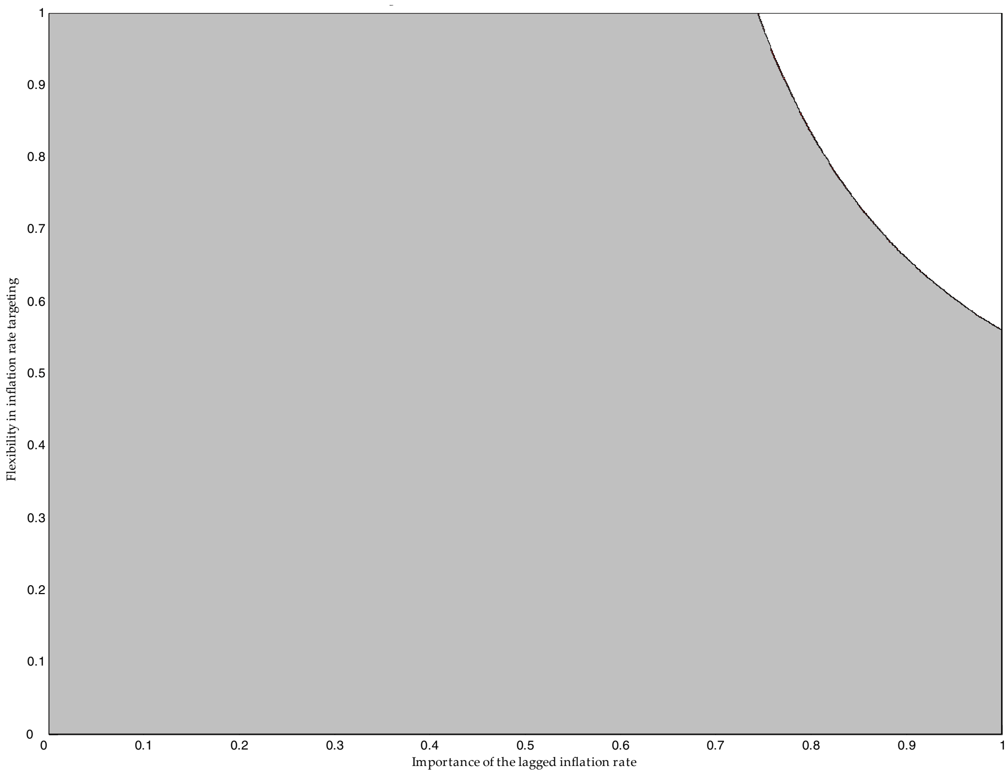

Figure A.10. Region for a determinate REE that is stable under learning (see light area) and region when there is no stable REE (see white area)

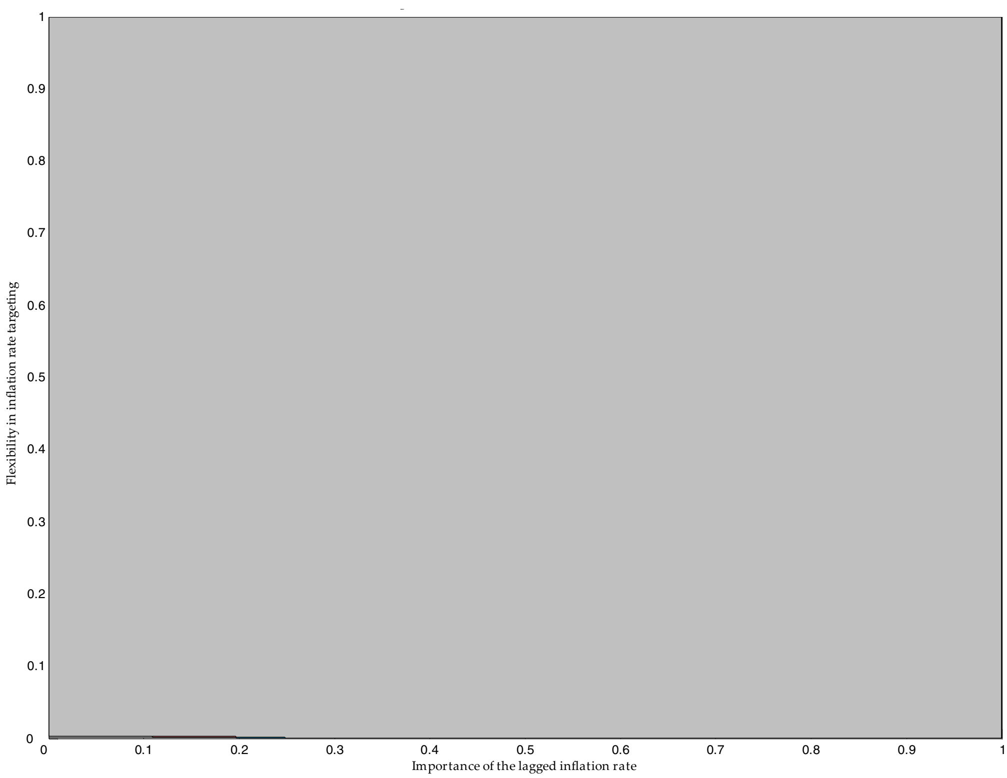

Figure A.11. Region for a determinate REE that is stable under learning (see light area) and region for an indeterminate REE (see dark area)

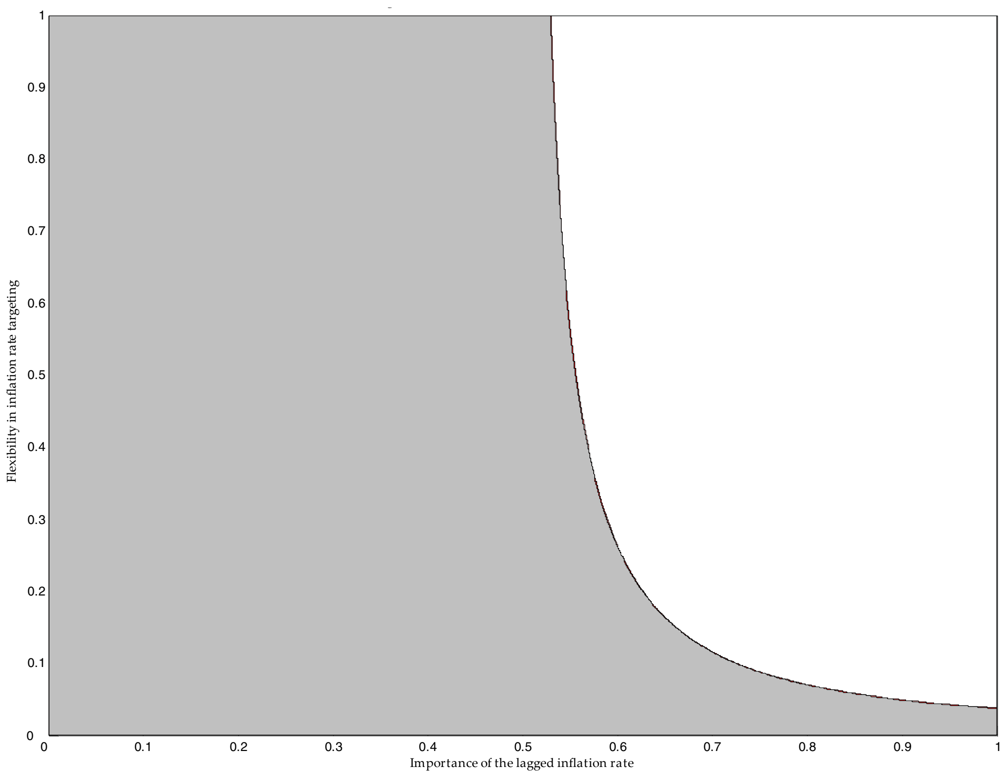

Figure A.12. Region for a determinate REE that is stable under learning (see light area) and region when there is no stable REE (see white area)

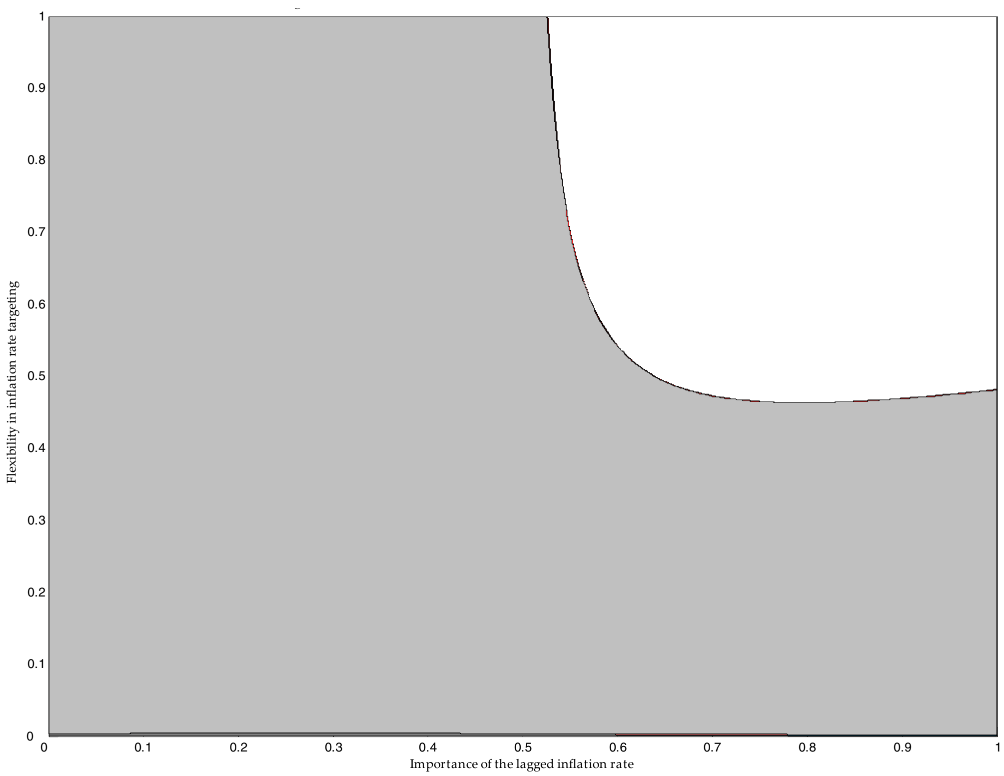

Figure A.13. Region for a determinate REE that is stable under learning (see light area) and regions for an indeterminate REE (see dark area) and no stable REE (see white area)

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