BANCA D'ITALIA
EUROSISTEMA

Temi di discussione

(Working Papers)

Optimal robust monetary policy with parameters and output gap uncertainty

by Adriana Grasso and Guido Traficante

June 2021

Number 1339

BANCA D'ITALIA
EUROSISTEMA

Temi di discussione

(Working Papers)

Optimal robust monetary policy with parameters and output gap uncertainty

by Adriana Grasso and Guido Traficante

Number 1339 - June 2021

ISSN 1594-7939 (print)
ISSN 2281-3950 (online)

Printed by the Printing and Publishing Division of the Bank of Italy

OPTIMAL ROBUST MONETARY POLICY WITH PARAMETERS AND OUTPUT GAP UNCERTAINTY

by Adriana Grasso* and Guido Traficante°

Abstract

This paper studies optimal robust monetary policy when the central bank observes potential output imperfectly and has Knightian uncertainty about the intertemporal elasticity of substitution and the slope of the Phillips curve. The literature on optimal robust monetary policy has focused either on the imperfect observability of some variables or on parameter uncertainty. We characterize robust monetary policy analytically for the two types of uncertainty and show that in general, uncertainty calls for a more aggressive monetary policy reaction compared with the certainty case.

JEL Classification: E32, E52.
Keywords: potential output, parameter uncertainty, optimal monetary policy, Taylor rule.
DOI: 10.32057/0.TD.2021.1339

Contents

* Bank of Italy, Directorate General for Economics, Statistics and Research - Economic Outlook and Monetary Policy.

° European University of Rome.

1 Introduction[1]

Central banks operate under uncertainty. The difficulty to understand the sources of shocks, to gauge the real value of some parameters or to measure some state variables are some notable examples of uncertainty. Conducting monetary policy in such an environment is complex since its effects are less predictable and the most appropriate response to shocks is harder to select. Successful policy making might require to avoid an overly aggressive monetary policy reaction in some situations, while opting for a firmer response in others. An extreme form of uncertainty is the "Knightian" uncertainty, which refers to situations where the probability distributions of economic outcomes is unknown. As to date, the shock associated with the pandemic can be seen as an example of Knightian uncertainty.[2]

In this paper, we consider two types of uncertainty. The central bank does not know the true model describing the economy and does not observe the level of some important macroeconomic variables.[3] Our objective is twofold. First, we aim at characterizing optimal robust monetary policy rules. Second, we are interested in deriving the conditions under which the central bank should be more cautious or more aggressive relative both to the case with no uncertainty and to the case in which only the parameters of the model are uncertain.

The baseline model is a standard forward-looking New Keynesian model summarized by an Euler equation and a Phillips curve. In particular, we build on Giannoni (2002), who studies optimal monetary policy under Knightian uncertainty on the intertemporal elasticity of substitution (IES) and on the slope of the Phillips curve, and add a misspecified output gap to his model. This feature reflects the fact that potential output is a very difficult variable to observe in real time but at the same time it is important for the conduct of monetary

[1]We are grateful to two referees, Giuseppe Ferrero, Kohei Hasui, Stefano Neri, Mario Pietrunti, Alessandro Secchi, Peter Tillmann, Andrea Tiseno and Paolo Vitale for useful comments and fruitful discussions. We also thank Marc Giannoni for sharing with us the codes of his paper. The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the position of Banca d'Italia or the Eurosystem.

[2]As emphasized by Stephen Poloz, former Bank of Canada's Governor, "*The pandemic is an example of Knightian uncertainty that will also force us to reconsider many fundamental ideas about how our economy can and should function*".

[3]Otmar Issing in his speech at the conference on "*Monetary policy-making under uncertainty*" in 1999 stated " *Among the various forms of uncertainty that central bankers face, the uncertainty about how the policy instrument affects inflation and economic activity - the monetary transmission mechanism - and the uncertainty about the current state of the economy - the data - appear to weigh particularly heavily*".

policy. Because of the joint uncertainty on the IES and the slope of the Phillips curve on one hand and on potential output on the other hand, the central bank cannot back out the correct potential output from observing inflation and the natural rate. In this environment, the central bank aims at avoiding the worst realizations of output gap, IES and slope of the Phillips curve. Moreover, as in Giannoni (2002), we assume that the central bank faces a trade-off between the stabilization of inflation and the output gap on one hand, and nominal interest rate smoothing on the other hand. Because of parameter uncertainty, the trade-off is difficult to quantify, while uncertainty on potential output induces doubts in the effectiveness of monetary policy in closing the output gap. We solve the model so that the central bank formulates a robust policy that limits the central bank loss in the most adverse scenario, i.e. one which exhacerbates the consequences of the shocks to the natural rate.

Our paper is related to two strands of literature that study the impact that uncertainty has on monetary policy. The first one is about the consequences of an imperfect estimation of potential output or an unobservable output gap. Ehrmann and Smets (2003) show that, with unobservable potential output, the central bank cannot distinguish in real time which shock hits the economy and this results in policy mistakes. Similarly, Cukierman and Lippi (2005) model a situation in which the central bank is unable to disentangle how changes in potential output due to oil shocks transmit to output fluctuations. As a consequence, monetary policy becomes excessively loose compared to the case of full information. This line of reasoning is used to explain policy mistakes in the 1970s, as in Orphanides (2001) and Orphanides (2003b). Lippi and Neri (2007) estimate a small scale new keynesian model for the euro area under the assumptions of imperfect information and discretionary monetary policy, showing that the central bank pursues interest-rate smoothing and inflation stabilization much more than output gap stabilization. More recently, Tillmann (2014) finds that appointing a conservative central banker limits the cost of uncertainty about potential output.

The second strand of literature to which our paper is related is parameter uncertainty. The starting point of the theoretical literature is Brainard (1967): the so called "Brainard principle" prescribes that central bank must respond more cautiously to shocks in presence of parameter uncertainty that makes it difficult to assess the monetary policy transmission. Using a backward-looking model of the economy, Söderström (2002) finds that when there is uncertainty about the persistence of inflation, it may be optimal for the central bank to respond to shocks more aggressively, while uncertainty about other parameters dampens the policy response. Instead, Ferrero et al. (2019) show that, if the model is forward looking and uncertainty concerns the slope of the Phillips curve, the optimal monetary policy may be more cautious or more aggressive than in the case of complete information, depending on the degree of persistence of the cost-push shock. We extend the analysis in Giannoni (2002) which, under uncertainty about the slope of the Phillips curve and the Euler equation, finds the conditions under which the central bank must respond more strongly to inflation than under certainty.[4]

We contribute to the literature by deriving analytical results for robust monetary policy rules under uncertainty both on the parameters and on some variables of the model. To the best of our knowledge, there are no papers which simultaneously consider these two sources of uncertainty. In particular, adding uncertainty on potential output is important from a policy point of view, as estimates of output gap are usually noisy, and particularly in recent years. In this environment, we evaluate the strength of the monetary policy response relative to the certainty case and to Giannoni (2002), and discuss the implications of adopting the robust policy in terms of interest rate setting.

We assume that the policymaker is unable to formulate a probability distribution over alternative outcomes for potential output and for two unknown structural parameters, the intertemporal elasticity of substitution and the slope of the Phillips curve.[5] As commonly done in the literature, we implement this type of Knightian uncertainty as a game between the central bank and a malevolent hypothetical evil agent whose aim is to set the value for output gap and the unknown parameters that maximize the objective loss function.[6] Therefore, the central bank's objective is to minimize the impact of the worst-case realization of output gap, intertemporal elasticity of substitution and slope of the Phillips curve. The only shock in the model is to the natural rate of interest, and represents all non-monetary disturbances that affect inflation and output gap.

[4]Similar results are found by Onatski and Stock (2002) and Onatski and Williams (2003).

[5]We focus on these two parameters because they are key in the transmission of monetary policy. As to the slope of the Phillips curve, its uncertainty is mainly due to the mixed evidence about the degree of price stickiness, as shown in Bils and Klenow (2004) and Nakamura and Steinsson (2013).

[6]On Knightian uncertainty on potential output see Tillmann (2014).

In terms of optimal robust policy we find that, as in Giannoni (2002), monetary policy does not completely offset the shock to the natural rate when the intertemporal elasticity of substitution and the slope of the Phillips curve are uncertain; this is due to the fact that the central bank cares about fluctuations in inflation, output gap and the nominal rate, and adjusting the latter as much as the natural rate would imply that the other two quantities would be stabilized to a lesser extent. Adding a second layer of uncertainty to Giannoni (2002), specifically assuming that the output gap is estimated with some error, yields interesting results. Because of measurement errors in potential output, the policy rate does not necessarily increase after a positive shock to the natural rate, as it would be with only parameter uncertainty, but the direction of the adjustment depends on how confident the central bank is of its estimates. Uncertainty affects not only the size of the response of the economy to shocks, but also the direction. We show that the presence of two sources of uncertainty implies that the monetary policy response and the overall stance depend on (i) the relative persistence of the shock to the natural rate of interest and (ii) the relationship between how confident the central bank is of its estimate of potential output and the weight attached to output gap stabilization in the central bank's loss function. For instance, when the persistence of the shock to the natural rate is relatively low and the central bank cares more about stabilizing the output gap, a positive shock to the natural rate does not necessarily imply an upward revision of the nominal rate, as it would be without uncertain potential output (this last result is in Giannoni, 2002). Intuitively, we interpret this as follows: when the shock to the natural rate has low persistence, the central bank believes that this will fade out soon. Because it focuses more on stabilizing the output gap, whenever there is a high distortion of potential output, the central bank might misinterpret the source of the shock and believe it is a shock to potential output, hence reducing the nominal rate.

We then implement the robust non inertial equilibrium in terms of a simple Taylor-type interest setting rule and evaluate the magnitude of the response of the interest rate to fluctuations in inflation. That is, we study the sensitivity of the inflation coefficient to the unknown parameters and to the degree of uncertainty about potential output and discuss equilibrium determinacy. We again complement what Giannoni (2002) has found, which is that in general the central bank must respond more aggressively to movement in inflation under parameter uncertainty than in absence of uncertainty. Adding uncertainty on potential output, we show that the monetary policy rule prescribes that in general the policy rate reacts even more strongly to fluctuations in inflation. This is because this second layer of uncertainty amplifies the effect that exogenous shocks would have on the economy, so that the policymaker must respond more strongly to offset them. Overall, the more uncertain the central bank is about the measure of potential output, the stronger the response of the interest rate to inflation fluctuations will be.

The paper is organized as follows. In Section 2 we present the model, before describing optimal robust monetary policy under discretion in Section 3, together with a numerical illustration of the latter. We then implement the robust optimal policy through a Taylor rule in Section 4 before concluding.

2 The Model

We consider a simple structural DSGE model derived from first principles. The main equations are the intertemporal IS equation and the new Keynesian Phillips' curve respectively:

$$x_t = E_t x_{t+1} - \frac{1}{\sigma}\left(i_t - E_t \pi_{t+1} - r_t^n\right) \tag{1}$$

$$\pi_t = \kappa x_t + \beta E_t \pi_{t+1} \tag{2}$$

Equation (1) can be viewed as a log-linear approximation to the representative household's Euler equation for optimal timing of consumption in the presence of complete financial markets, while (2) can be interpreted as a log-linear approximation to the first-order condition for the optimal price-setting decision taken by firms. The endogenous variables of the model are the output gap x_t and the inflation rate π_t, while the policy instrument is the nominal interest rate i_t. The exogenous disturbance r_t^n represents Wicksell's natural rate of interest, that is, the real interest rate that equates output to its natural level or, alternatively, the interest rate that would prevail in equilibrium under flexible prices. It is modeled as a first-order autoregressive process:

$$r_t^n = \rho r_{t-1}^n + \varepsilon_t \quad 0 \leq \rho < 1 \quad \varepsilon_t \sim \text{white noise} \tag{3}$$

Perturbations to the natural rate of interest represent all non-monetary disturbances that affect output gap and, in turn, inflation. For instance, a temporary increase in r_t^n could reflect a temporary exogenous increase in aggregate demand or, alternatively, a temporary decrease in the natural level of output. Moreover, non-monetary perturbations affect inflation and output gap only if the interest rate controlled by the central bank – the nominal interest rate less expected inflation – is higher or lower than the natural rate of interest. The structural parameters $\sigma, \kappa > 0$ represent the inverse of the intertemporal elasticity of substitution and the slope of the short-run aggregate supply curve respectively. Finally, β is the time discount factor.

The information structure is asymmetric with only the private sector having full information. This feature reflects the fact that the model equations are structural, hence invariant to the policy chosen by the central bank, and all members of the private sector have a common information set. As a consequence, private agents have full information about the relevant variables and perfectly know the structure of the economy.[7] Central bank's uncertainty lies in Knightian uncertainty about σ, κ and misspecification of the output gap x_t in (2). We assume that the central bank is unable to formulate a probability distribution over σ, κ and x_t: it considers many probability measures and is averse to uncertainty.[8] Under these hypotheses, the policymaker's problem is to minimize the loss in the worst-case realization of unknown parameters and misspecified output gap.[9] Uncertainty is then twofold, in parameters and observables. As for parameter uncertainty, the central bank has to formulate optimal policy knowing that the true values of σ and κ lie in the following intervals:

$$\sigma \in [\sigma_l, \sigma_h] \qquad \kappa \in [\kappa_l, \kappa_h] \tag{4}$$

[7] This argument is found also in Svensson and Woodford (2004).

[8] We follow the approach in Gilboa and Schmeidler (1989).

[9] An alternative is the Bayesian approach where it is possible to formulate a probability distribution for unknown parameters.

Furthermore, the central bank also fears distortions to its estimate of the output gap, due to the fact that potential output is unobservable in real time without a sizable measurement error. This feature is modeled by defining the measure of potential output, $\hat{x}_t^n$, equal to the true target x^n (which we assume to be zero without loss of generality) plus a misspecification y_t, which we assume to be serially uncorrelated to facilitate an analytical solution

$$\hat{x}_t^n = x^n + y_t \tag{5}$$

As we said before, importantly, in contrast to the central bank, the private sector is assumed to know the true output gap, hence the distortion y_t does not enter the structural equations (1) and (2), but it will affect monetary policy. To solve the model, we proceed as in Giannoni (2002) and look for the Nash Equilibrium (NE) of a game between the policymaker and a fictitious evil agent that sets σ, κ and y_t with the aim of maximizing the central bank's loss function under the constraint that (4) holds and that there exists a finite budget of potential misspecification ω for y_t[10]

$$y_t^2 \leq \omega \tag{6}$$

We assume that the central bank minimizes the following loss function:

$$\pi_t^2 + \lambda_x (x_t - y_t)^2 + \lambda_i i_t^2 \quad \lambda_x, \lambda_i > 0 \tag{7}$$

where λ_x and λ_i are the weights that the central bank gives to output gap and interest rate stabilization, respectively. This loss function suggests that the central bank is interested in minimizing the variability of inflation, the output gap and the nominal interest rate.[11] A central bank which does not include the interest rate in its objective function can perfectly

[10] See Hansen and Sargent (2008) for a thorough explanation of the methodology.

[11] We include the interest rate in the objective function of the central bank to follow Giannoni (2002) as closely as possible. This feature captures the observed tendency of policymakers to smooth interest rates. Some explanations for interest rate smoothing include the central bank's tradeoff between its concern for stability of the financial system and for price stability (Cukierman, 1991); interest rate smoothing in forward-looking models as an anchor for expectations results in lower volatilities of inflation and output (gap) as well as of the interest rate (Levin et al., 1999, Woodford, 1999); and also reflects uncertainty regarding data due to revisions (Orphanides, 2003a). A gradual response may also be in order given uncertainty regarding the parameters of the economy (Sack, 2000), the striving for consensus about interest rate decisions (Sack and Wieland, 2000), or avoiding the (zero) lower bound (Woodford, 2011).

stabilize inflation and the output gap by setting $i_t = r_t^n$; this may generate a marked volatility in the interest rate. In our setting, the central bank still aims at stabilizing inflation and output gap, but it does not like to move the nominal interest rate as much as the natural rate of interest. As a consequence, the desire to smooth the nominal interest rate creates a tension between the stabilization of inflation and output gap on one hand, and of the nominal interest rate on the other. Note that, due to the misspecification of potential output, the central bank evaluates output in (7) in deviations from a biased target.

Here we briefly specify the steps that we follow to solve the model. Let L be the policymaker's loss function, $E \subset \mathbb{R}^m$ a given (known) compact set of possible structural parameters, Ψ a set of policy rules such that there is a unique bounded equilibrium process $q(\psi, \eta)$ for all $\psi \in \Psi, \eta \in E$. We assume that the policymaker chooses the policy rule $\psi^* \in \Psi$ to minimize his loss, $L(\psi, \eta)$, knowing that a malevolent agent tries to hurt him as much as possible. The other player chooses the vector of structural parameters $\eta^* \in E$ to maximize the policymaker's loss, knowing that the policymaker is going to minimize it. The solution strategy proposed by Giannoni (2002) involves the four following steps.

1. Optimal equilibrium for given set of parameters η. We determine the parameterization $f^*(\eta)$ of the equilibrium process that solves the policymaker's problem, minimizing the loss function for any given $\eta \in E$.

2. Candidate minmax equilibrium. We partially differentiate the policymaker's Lagrangian with respect to η, and use Lemma 3 in Giannoni (2002) to determine a candidate worst-case parameter vector η^*. Using the results of step 1, we determine the vector $f^*(\eta^*)$ parameterizing the *candidate* minmax equilibrium $q(f^*(\eta^*))$.

3. Robust optimal policy rule. We look for a policy rule ψ^* that implements the candidate minmax equilibrium and we verify that $\psi^* \in \Psi$, i.e., that the policy rule results in a unique bounded equilibrium process $q(\psi^*, \eta)$ for all $\eta \in E$.

4. Existence of global Nash Equilibrium (NE). We verify that (ψ^*, η^*) is a global NE by checking that the candidate worst-case parameter vector η^* maximizes the loss L on the whole constraint set E given the policy rule ψ^*.

3 Optimal Monetary Policy Under Discretion

In this section we derive optimal robust monetary policy under discretion. In other words, we assume that a commitment is not feasible for the central bank, which optimizes the loss function (7) every period under the constraints represented by the IS and the Phillips curve, and taking into account the uncertainty surrounding the Phillips curve slope, output gap elasticity to the interest rate and the measurement of output gap.

The solution strategy involves using a min-max approach through which the central bank tries to minimize the impact of the worst-case realization of both parameters and potential output.[12] In setting the policy rate, the central bank acts as if a malevolent hypothetical evil agent sets σ, κ and the distortion to potential output y_t with the objective to maximize the central bank's loss. Formally, the objective function becomes

$$\min_{\pi_t, x_t, i_t} \max_{\sigma, \kappa, y_t} \quad \pi_t^2 + \lambda_x \left(x_t - y_t\right)^2 + \lambda_i i_t^2 \tag{8}$$

Notice that the distortion on potential output in the loss function does not show up in the structural equations because of the asymmetric information set between the central bank, who has uncertainty on two parameters and potential output, and the private sector who has full knowledge.

We solve the model by conjecturing that the equilibrium values of π_t, i_t, x_t and y_t depend only on the natural interest rate:[13]

$$\pi_t = f_\pi r_t^n \quad x_t = f_x r_t^n \qquad y_t = f_y r_t^n \quad i_t = f_i r_t^n \tag{9}$$

where the equilibrium response coefficients f_π, f_x, f_y and f_i must be determined by minimizing the loss function. Accordingly, we can take into account (9) in (1) and (2), obtaining the following feasibility constraints:

$$(1-\rho) f_x + \frac{1}{\sigma}\left(f_i - \rho f_\pi - 1\right) = 0 \tag{10}$$

[12] We use the method proposed in Giannoni (2002), which expresses the problem of deriving robust optimal monetary policy rules when the true model is unknown as a zero-sum two-player game.

[13] Because the objective is quadratic and the constraints are linear in all variables, we may, without loss of generality, restrict our attention to linear solutions.

$$(1-\beta\rho)f_\pi - \kappa f_x = 0 \tag{11}$$

As we are considering non inertial plans, the previous problem can be reformulated through the minimization of the following policymaker's Lagrangian[14]

$$\mathcal{L}_t = f_\pi^2 + \lambda_x \left(f_x - f_y\right)^2 + \lambda_i f_i^2 - \theta f_y^2 + \phi_1 \left[(1-\rho)f_x + \frac{1}{\sigma}\left(f_i - \rho f_\pi - 1\right)\right] + \phi_2 \left[(1-\beta\rho)f_\pi - \kappa f_x\right] \tag{12}$$

where ϕ_1 and ϕ_2 are the Lagrange multipliers. The parameter $\theta > 0$ is inversely related to the budget of potential misspecification of the evil agent ω and measures the level of confidence the central bank has in its estimate of potential output. Put differently, θ determines the set of models available to the evil agent against which the policymaker wants to be robust (see Leitemo and Söderström, 2008). When $\theta \to \infty$ the central bank has no uncertainty about potential output and estimates it correctly.[15] The first-order conditions of the problem are:

$$2f_\pi - \frac{\phi_1\rho}{\sigma} + \phi_2(1-\beta\rho) = 0 \tag{13}$$

$$2\lambda_x \left(f_x - f_y\right) + \phi_1(1-\rho) - \kappa\phi_2 = 0 \tag{14}$$

$$-2\lambda_x \left(f_x - f_y\right) - 2\theta f_y = 0 \tag{15}$$

$$2\lambda_i f_i + \frac{\phi_1}{\sigma} = 0 \tag{16}$$

From (15), f_y can be expressed as a function of f_x:

$$f_y = -\frac{\lambda_x}{\theta - \lambda_x} f_x$$

showing that in the limit case of certainty about potential output, the optimal response to the misspecified output gap is zero, i.e. the evil agent knows that the central bank has perfect information about potential output and so her best response is to do nothing to the measurement error. Notice that evil agent's best response does not necessarily imply that y_t

[14]The solution procedure shown below is equivalent to solve for the discretionary equilibrium and then show how each endogenous variable is related to the natural rate of interest.

[15]In other words, the evil agent chooses a value of $y_t = 0$. As a general guide to interpret θ, Hansen and Sargent (2008) base it on a detection error probability approach.

is at one corner of the budget of potential misspecifications ω. Not only the response depends on the degree of confidence on the estimates of potential output, but also on the weight that the central bank puts on output gap stabilization, λ_x, and on the optimal response to output gap of the central bank.

Combining all the first-order conditions to eliminate ϕ_1 and ϕ_2, the following implementability condition must hold

$$f_\pi + \rho\lambda_i f_i + \frac{\theta\lambda_x f_x(1-\beta\rho)}{\kappa\left(\theta-\lambda_x\right)} - \frac{\sigma\lambda_i f_i(1-\rho)(1-\beta\rho)}{\kappa} = 0 \tag{17}$$

which, together with (10) and (11), determines the equilibrium response coefficients f_π, f_x, f_y and f_i:

$$f_\pi = \frac{\lambda_i\kappa\left(\theta-\lambda_x\right)\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]}{\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2} \tag{18}$$

$$f_x = \frac{\lambda_i(1-\beta\rho)\left(\theta-\lambda_x\right)\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]}{\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2} \tag{19}$$

$$f_y = -\frac{\lambda_i\lambda_x(1-\beta\rho)\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]}{\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2} \tag{20}$$

$$f_i = \frac{\theta\lambda_x\left(1-\beta\rho\right)^2+\left(\theta-\lambda_x\right)\kappa^2}{\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2} \tag{21}$$

Notice that these equilibrium conditions generalize the optimal noninertial plan in Giannoni (2002) and collapse to it when $\theta \to \infty$. In the latter case output gap is observed without error and $f_y = 0$. If the output gap measurement is very noisy – consider for example the case of $\theta \to 0$ – the evil agent will set the distortion f_y exactly equal to the opposite of the central bank's response to output gap. Now we study the sign of the equilibrium response coefficients, evaluating how it is affected by parameter uncertainty coupled with output gap misspecification. The transmission of a shock to the natural rate is deeply related to its persistence ρ. Before considering the general case, for the sake of clarity, we will discuss the case of a temporary shock to the natural rate (with $\rho = 0$) and we will compare the results in the uncertainty case with those in Giannoni (2002) and under certainty.

Optimal discretionary policy for a temporary shock. Here we evaluate the optimal robust policy when the shock to the natural rate of interest produces no persistent effects in the economy. In this case, the optimal response of the endogenous variables (18) – (21) simplify in the following expressions:

$$f_\pi = \frac{\lambda_i \kappa \sigma (\theta - \lambda_x)}{(\theta - \lambda_x)(\kappa^2 + \lambda_i \sigma^2) + \theta \lambda_x} \tag{22}$$

$$f_x = \frac{\lambda_i \sigma (\theta - \lambda_x)}{(\theta - \lambda_x)(\kappa^2 + \lambda_i \sigma^2) + \theta \lambda_x} \tag{23}$$

$$f_y = -\frac{\lambda_i \lambda_x \sigma}{(\theta - \lambda_x)(\kappa^2 + \lambda_i \sigma^2) + \theta \lambda_x} \tag{24}$$

$$f_i = \frac{\theta \lambda_x + (\theta - \lambda_x)\kappa^2}{(\theta - \lambda_x)(\kappa^2 + \lambda_i \sigma^2) + \theta \lambda_x} \tag{25}$$

It can be easily shown that the optimal response of the nominal interest rate, inflation and output gap to a positive shock is positive whenever the degree of uncertainty in the measurement of potential output is larger than the weight attached to the stabilization of the output gap ($\theta > \lambda_x$); in this case the central bank correctly gauges a positive shock, understanding that it will increase the output gap and, in turn, raise inflation. The central bank will react by increasing the interest rate less than proportionally than the natural rate. Notice that monetary policy here is accommodative as the real interest rate ($i_t - E_t \pi_{t+1}$) is smaller than the natural rate r_t^n.[16]

The same will happen when the central bank is very uncertain of its measurement of potential output (namely for $\theta < \frac{\lambda_x \kappa^2}{\kappa^2 + \lambda_x}$) although, in this case, the interest rate response will be weaker than before. The smaller fluctuactions in the interest rate are in turn coupled with the stronger movements for inflation and output gap.

On the other hand, when the confidence in the measurement of potential output is smaller than the weight attached to output gap stabilization, there are cases in which the policymaker erroneously interprets the shock to the natural rate as deflationary instead of inflationary. The wrong interpretation implies that the relationship of endogenous variables with the natural rate in equilibrium can be distorted because fluctuations are not too persistent and

[16] In order to prove this finding, use the definition of real interest rate $i_t - E_t \pi_{t+1}$ and equation (10).

real-time output gap measurement is noisy[17]. The central bank can observe the natural rate and inflation but it cannot back out potential output because of parameter uncertainty. Whenever the persistence in the shock to the natural rate is low, uncertainty on potential output is sizable and the central bank wants to stabilize the output gap, it can wrongly interpret the source of the shock, thinking it is not to the natural rate but to the output gap. This then induces the policymakers to cut interest rates and inflation goes up. So after a positive shock to the natural rate, the nominal interest rate, inflation and output gap move in different directions, namely whenever the former increases the latter decrease and viceversa.[18]

3.1 The General Case

We now look at the general case. First, we consider the response of the nominal interest rate to shocks hitting the natural rate. The latter depends on the relative values of parameters in (21). In particular, it can be shown that given two coefficients χ and Γ defined below:

$$\begin{aligned} f_i \geq 0 \iff \theta \leq \chi\lambda_x,\ \theta > \Gamma\lambda_x \quad & 0 < \Gamma \equiv \frac{\kappa^2 + \lambda_i\left[\sigma(1-\rho)(1-\beta\rho) - \rho\kappa\right]^2}{\kappa^2 + \lambda_i\left[\sigma(1-\rho)(1-\beta\rho) - \rho\kappa\right]^2 + \lambda_x\left(1-\beta\rho\right)^2} \leq 1 \\ f_i \leq 0 \iff \chi\lambda_x \leq \theta \leq \Gamma\lambda_x \quad & 0 < \chi \equiv \frac{\kappa^2}{\lambda_x(1-\beta\rho)^2 + \kappa^2} < 1, \quad \chi < \Gamma \end{aligned} \tag{26}$$

We can observe that the optimal nominal interest rate does not necessarily increase after a positive shock to the natural rate, but its response depends on the degree of confidence the central bank has in the measurement of potential output. This extends the result in Giannoni (2002), in which the optimal response coefficient for the nominal interest rate is always positively correlated with the shock. The author also finds that the latter is lower than 1, i.e. the nominal rate adjusts less than the natural rate, a characteristic that is preserved in our case, even with an additional layer of uncertainty. Finally, the sign of f_i does not depend on the persistence of the shock, as we could already gauge by the discussion in the

[17] This occurs when $\theta \in (\frac{\lambda_x\kappa^2}{\kappa^2+\lambda_x}, \lambda_x)$ in the case of a purely temporary shock.

[18] These findings also hold in the general version of the model, where the shock to the natural rate is persistent over time. In the latter case, however, it will be harder to present simple analytical results and we will use simulations.

previous section.

Instead, we saw that the persistence of the shock matters for the other coefficients. Below, we study how the sign of f_π and f_x changes as function of ρ and θ, and what this implies for monetary policy. We start by analyzing the case in which the fluctuations in the natural rate are not too persistent relative to the ratio σ/κ. Absent the uncertanty on the measurement of potential output, Giannoni (2002) shows that the response coefficients to inflation and output gap are positive. In our case, however, this condition is not sufficient to determine the sign, as we have to take into account the uncertainty coming from the misspecification of potential output. In fact, we can prove that for both coefficients to be positive the desire for robustness θ must also be larger than the weight attached to output gap stabilization λ_x in the loss function. This second constraint arises because there is not only parameter uncertainty, but there is also uncertainty about the true value of the potential output. More in detail, when $\theta > \lambda_x$, then $f_i > 0$[19] and there is a positive correlation of inflation and output gap response with the shock.

If instead $\theta < \lambda_x$, f_π and f_x are positive if $\theta < \Gamma\lambda_x$ and negative if $\Gamma\lambda_x < \theta < \lambda_x$, where Γ is defined as in equation (26).[20] In these cases the estimate of potential output is very noisy and the central bank's desire to stabilize the output gap is greater than her confidence in that estimate. She may believe that the shock is on potential output and not on the natural rate, and decide to decrease the interest rate. This result extends what we already described in the case of a temporary shock, i.e. that whenever the confidence in the measurement of potential output is smaller than the weight attached to the stabilization of the output gap, there are cases in which the policymaker erroneously interprets the shock to the natural rate as deflationary instead of inflationary and reacts by lifting the interest rate while inflation and output gap decrease. Whenever f_π is negative, as we pointed out in the previous section, even though the nominal rate increases less than the natural rate, monetary policy is restrictive.

The stance is often restrictive in the case of more persistent shocks relative to the ratio σ/κ; this is true whenever $\theta > \lambda_x$ for example, i.e. whenever the bank is relatively confident

[19] f_i is positive because $\Gamma < 1$, see equation (26).

[20] If $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\theta < \lambda_x$, then the numerator of f_π is negative, while the denominator is positive if $\theta > \Gamma\lambda_x$. For f_x we use the relation $f_x = \frac{1-\beta\rho}{\kappa} f_\pi$.

in its estimate on potential output. In this case the central bank reacts to a positive shock to the natural rate by increasing the nominal interest rate, reducing inflation and output gap. Whenever the desire to stabilize output prevails ($\theta < \lambda_x$), the coefficients f_π and f_x are negative if $\theta < \Gamma\lambda_x$ and positive if $\Gamma\lambda_x < \theta < \lambda_x$.

3.2 Determining the Equilibrium Structural Parameters

In the previous sections we have determined the equilibrium processes for the endogenous variables (inflation, output, and the interest rate) that achieve the lowest value of the loss criterion given a generic σ and κ. Following the solution method in Giannoni (2002), we now determine the structural parameters that characterize the candidate minmax equilibrium. The author proves that in order to choose the candidate equilibrium values of σ and κ in the intervals $[\sigma_l, \sigma_h]$ and $[\kappa_l, \kappa_h]$ respectively, one has to differentiate the policymaker Lagrangian with respect to the parameters. Depending on the sign of the derivatives, the optimal response of the evil agent will be to set the uncertain parameters at one of the boundaries of its interval.[21]

By differentiating (12) with respect to σ, considering (16), we have

$$\frac{\partial \mathcal{L}_t}{\partial \sigma} = -\frac{\phi_1}{\sigma^2}\left[f_i - \rho f_\pi - 1\right] = \frac{2\lambda_i f_i}{\sigma}\left[f_i - \rho f_\pi - 1\right] \tag{27}$$

This, together with (11), implies that

$$\begin{aligned} \frac{\partial \mathcal{L}_t}{\partial \sigma} &= -\Theta(1-\rho)\left\{\lambda_i(1-\beta\rho)\left(\theta-\lambda_x\right)\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]\right\} \\ \Theta &\equiv \frac{2\lambda_i\left[\theta\lambda_x\left(1-\beta\rho\right)^2+\left(\theta-\lambda_x\right)\kappa^2\right]}{\left[\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2\right]^2} \end{aligned} \tag{28}$$

The derivative of the Lagrangian with respect to κ is

$$\frac{\partial \mathcal{L}_t}{\partial \kappa} = -\phi_2 f_x$$

[21] Giannoni (2002) proves that the derivatives corresponds to the slopes of the Lagragian with respect to σ and κ evaluated at the candidate equilibrium.

where, considering (13)–(14) it is possible to write

$$\frac{\partial \mathcal{L}_t}{\partial \kappa} = 2f_x^2 \frac{\theta \lambda_x \rho(1-\beta\rho) + \sigma\kappa\left(\theta - \lambda_x\right)(1-\rho)}{\left[\sigma(1-\rho)(1-\beta\rho) - \rho\kappa\right]\left(\theta - \lambda_x\right)(1-\beta\rho)} \tag{29}$$

Once again, the sign of the derivatives, and therefore the equilibrium values for the structural parameters, depend on both the persistence of the shock and the confidence of the central bank in its estimate of potential output. For a wide range of values of potential output misspecification[22] and whenever the fluctuations in the natural rate are relatively less persistent than the ratio σ/κ, the worst situation for the policymaker occurs for large κ and small σ. This because we have stronger effects on output gap and inflation after shocks to the natural rate, as shown in the IS and the Phillips curve, when $\sigma = \sigma_l$ and $\kappa = \kappa_h$. If the shock is relatively more persistent, then the optimal robust equilibrium implies the lowest value for κ and the highest for σ. Notice that analytically there are four possible combinations of the ratio σ/κ but we only take the boundaries as candidates for equilibrium.

Summarizing, first we have determined the parameterization $f(\cdot)$ of the equilibrium processes for the endogenous variables that solve the policymaker's problem given a generic σ and κ. Second, we have found a candidate worst-case parameter vector (σ^*, κ^*) . These two steps together provide us with a candidate minmax equilibrium. The solution method proceeds by specifying a policy rule that *implements* the candidate equilibrium and to verify that this results is a unique bounded equilibrium. Before this last step described in Section 4, we present a numerical exercise to better understand our previous analytical results.

3.3 A Numerical Illustration

Table 1 provides the calibrated parameters of the model, which are taken from Giannoni (2002); in particular, we follow his calibration about the lower bound and the upper bound for σ and κ. The positive coefficient θ, which measures the level of confidence that the central bank has in its estimate of the potential output, varies according to how informed the central bank is. The certainty case corresponds to $\theta \to \infty$, while in case of very low confidence in the estimation of potential output, $\theta \to 0$.

[22] For example when $\theta > \lambda_x$. See Appendix A for the details.

Certainty case: baseline model			Parameter and potential output uncertainty		
Parameters	Value	Standard Error	Parameter	Lower Bound	Upper Bound
Structural			σ	0.0915	0.2227
β	0.99		κ	0.0168	0.0308
σ	0.1571	(0.0328)	θ	0	∞
κ	0.0238	(0.0035)			
Shock process					
ρ	0.35				
sd(r^n)	3.718				
Loss function					
λ_x	0.0483				
λ_i	0.2364				

Table 1: Structural parameters of the model

Figure 1 shows the value of the coefficients f_i, f_π, f_x when we vary the degree of uncertainty in the measurement of potential output and we choose the candidate equilibrium values of σ and κ in the respective intervals as in Section 3.2. The calibration we are using is such that perturbations to the natural rate are sufficiently transitory and we consider values of θ for which the three coefficients are positive.[23] The figure shows that, for the degree of uncertainty on potential output shown in the graph, the interest rate setting is more aggressive when the level of confidence is smaller compared to the case in which potential output is not misspecified and the difference between the two scenarios attenuates when the level of confidence increase. The more aggressive monetary policy stance dampens the on-impact response of inflation and output gap to disturbances in the natural rate of interest.

We interpret this finding with the idea that, in the case analyzed by Giannoni (2002), the policymaker can quantify the range in which output and inflation can vary, while this does not occur when potential output is misspecified; for the current parameterization (in particular whenever shocks are not so persistent) the central bank ”overreacts” to the shock as compared to the case with only parameter uncertainty.

Consider now a set of lower values for the confidence in the measurement of potential output, as shown in Figure 2, compared to those in Figure 1.[24] As shown above in the derivation about the optimal value of f_x and f_π, when the persistence of the shock is relatively

[23]Remember that what matters is the difference between θ and λ_x.

[24]In particular, we consider values such that $\theta < \lambda_x$

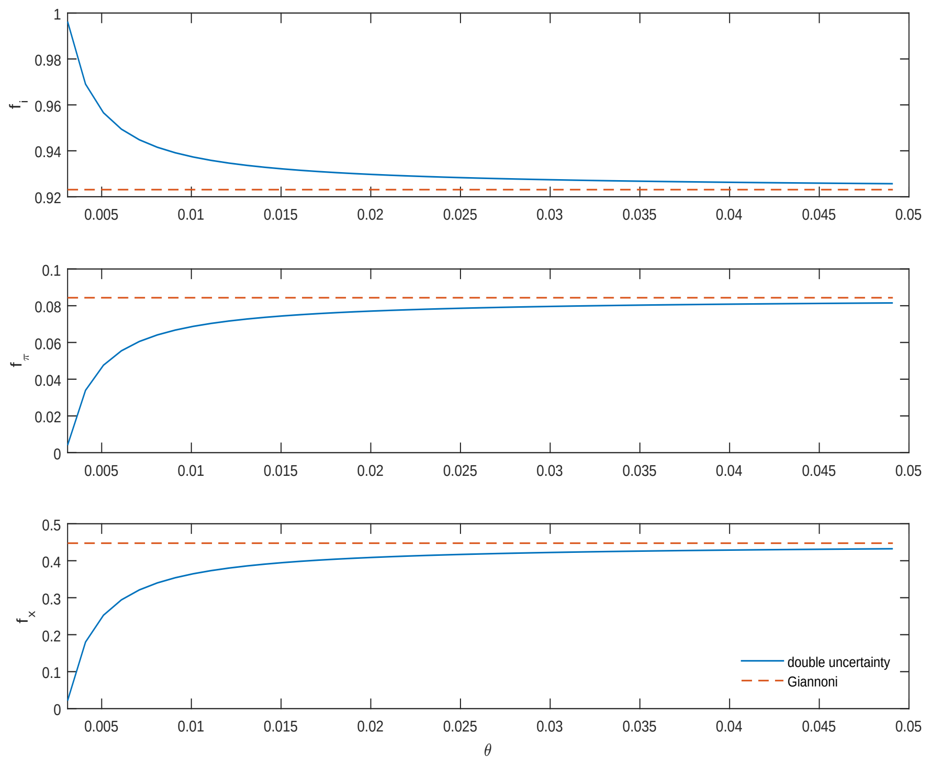

Figure 1: Optimal response of interest rate, inflation and output gap as function of the level of confidence in the measurement of potential output θ. The calibration is such that $\theta > \lambda_x$ and fluctuations in the natural rate have a relatively low persistence. The red dashed line shows the optimal coefficients in Giannoni (2002), where the output gap is observed without measurement error.

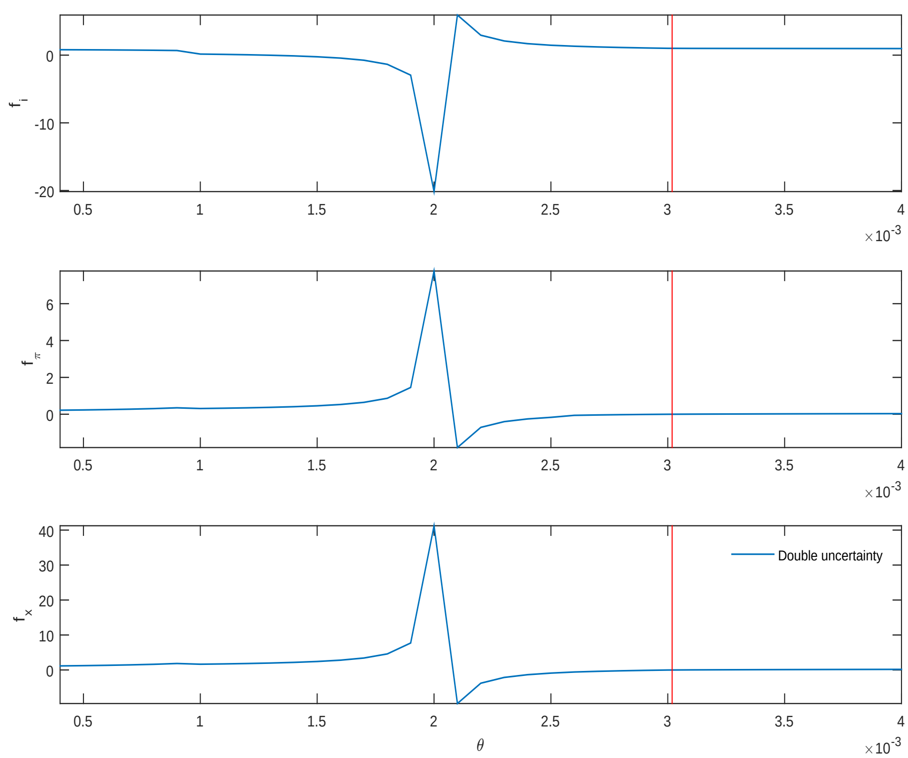

Figure 2: Optimal response of interest rate, inflation and output gap varying the level of confidence in the measurement of output gap θ. The calibration is such that fluctuations in the natural rate have a relatively low persistence. The vertical line indicates the value of λ_x. The coefficient in Giannoni (2002) are as in Figure 1 and are $f_i = 0.9231$, $f_\pi = 0.0844$ and $f_x = 0.4475$.

low and the uncertainty on the measurement of the output gap is high, the correlation of inflation and the output gap with shocks to the natural interest rate is not necessarily positive as in the previous case. Compared to the case of perfect information about the output gap, an increase in r_t^n could be misinterpreted and the policymaker may believe that the positive shock reduces potential output. This (wrong) assessment changes the candidate values of σ and κ in the optimal minmax equilibrium and, for the calibration we are considering, may suggest implausibly high (low) values for the response coefficients f. Indeed, the graph shows that there is a range of values for θ such that the policymaker lowers the interest rate after an increase in the natural rate.

4 Robust Optimal Taylor Rules

Motivated by the fact that central banks usually operate through interest rate rules, our aim is now to *implement* the candidate equilibrium with an interest rate rule that takes into account the uncertainty about model parameters and variables. We assume that monetary policy is characterized by the following Taylor rule

$$i_t = \psi_\pi \pi_t + \psi_x x_t \tag{30}$$

The optimal robust coefficients ψ_π and ψ_x are computed under the assumption that the central bank only knows that the parameters σ and κ lie in given intervals (4) and that potential output is misspecified as in (5). After substituting the interest rate rule (30) into the structural equations (1) and (2), the model can be written in matrix form as follows:

$$E_t z_{t+1} = A z_t + \alpha r_t^n \tag{31}$$

where $z_t \equiv [\pi_t, x_t]'$. The latter representation is obtained for any policy coefficients ψ_π, ψ_x and admits a unique solution if both the eigenvalues of A lie outside the unit circle, as in the Blanchard-Khan condition. Following Woodford (2011), it can be shown that the condition ensuring determinacy in a min–max approach is

$$\psi_\pi > 1 - \frac{1-\beta}{\kappa^*}\psi_x \tag{32}$$

where κ^* is the worst-case scenario value for κ. As (32) shows, for a given value of ψ_x, the worst-case value for κ affects the value of ψ_π, which dictates how much the interest rate has to respond to movements in inflation; when the robust policy prescribes a value $\kappa^* = \kappa_h$ larger than the true value of the parameter, then monetary policy must respond more aggressively to inflation compared to the full information case. An interest rate rule like (30) can be used to implement the optimal robust equilibrium under discretion; substituting the equilibrium responses of inflation, output, and the interest rate to the shock from (18) – (21) into the Taylor rule gives the feasibility constraint

$$f_i = \psi_\pi f_\pi + \psi_x f_x \tag{33}$$

By working out this condition, we can derive the optimal Taylor rule response coefficient to inflation as a function of ψ_x, the parameters (those distorted and those known with certainty) and the degree of confidence in the observation of potential output:

$$\psi_\pi = \frac{\theta\lambda_x (1-\beta\rho)^2 + (\theta-\lambda_x)\kappa^2}{\lambda_i\kappa(\theta-\lambda_x)[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa]} - \frac{\psi_x(1-\beta\rho)}{\kappa} \tag{34}$$

Any pair ψ_π, ψ_x satysfying (34) implements the candidate optimal discretionary minmax equilibrium, under the condition that it implies a unique bounded equlibrium, i.e. satisfies (32).

Finally, we verify that the policymaker's equilibrium responses and the equilibrium parameter vector (σ^*, κ^*) determine a global equilibrium, and hence that the corresponding rule (ψ_π^*, ψ_x^*) is a robust optimal Taylor rule. In order to do that, we need to check that the structural parameters (σ^*, κ^*) are the evil agent's best responses to (ψ_π^*, ψ_x^*) on the whole set of constraints (4), i.e. maximize the central bank's loss function on the whole set given the interest rate rule. Table 2 shows, for various levels of θ, both the maximum attained by the loss function over the whole constraint set and the value that the structural parameters take at that maximum. Note that in this case the confidence of the central bank in its estimate of potential output is always greater than the desire to stabilize the output gap ($\theta > \lambda_x$) and our candidates for equilibrium were (σ_l, κ_h), which is also a global equilibrium.

θ	Max(Loss)	Optimal Robust σ	Optimal Robust κ
0.004	3.11	0.0915	0.0308
0.005	3.07	0.0915	0.0308
0.006	3.05	0.0915	0.0308
0.008	3.03	0.0915	0.0308
0.010	3.03	0.0915	0.0308
0.040	3.02	0.0915	0.0308
0.400	3.02	0.0915	0.0308
4.000	3.02	0.0915	0.0308
40.000	3.02	0.0915	0.0308
100.000	3.02	0.0915	0.0308

Table 2: Maximum of loss function over the sets $\sigma \in [0.0915, 0.2227]$ and $\kappa \in [0.0168, 0.0308]$, and optimal values (σ^*, κ^*) in equilibrium for several levels of $\theta > \lambda_x$.

We now evaluate the interest rate response to a given shock by implementing the optimal robust equilibrium by means of the Taylor rule that we have constructed. In particular, for a given ψ_x, we study the sensitivity of the inflation coefficient to the unknown parameters σ and κ, and to the degree of uncertainty about potential output.[25] Next, we offer a comparison of the optimal Taylor rules under various scenarios of uncertainty, which will serve us to highlight whether the equilibrium is determinate or not.

Figure 3 shows the magnitude of ψ_π for different values of the two structural parameters σ and κ, when the central bank has no uncertainty about the potential output. The coefficient for output gap in the Taylor rule ψ_x is equal to 0.5. We can see that the response of the nominal rate to inflation is positive for all the values of σ and κ. In the certainty case, the higher σ and κ, the higher will be their impact on inflation, so the central bank reacts more aggressively the wider the set of possible models.

Instead, Figure 4 graphs the inflation coefficient for a lower value of θ compared to Figure 3: here θ is just slightly above λ_x, meaning that the correlation between the shock

[25]Note that this is equivalent to change the set of possible model misspecifications.

and inflation and output gap is still positive, but the central bank is less confident of its estimation of potential output than it was before. The figure shows that, all else equal, the presence of uncertainty about potential output measurement amplifies monetary policy response to inflation. A stronger reaction is needed to make the interest rate move more closely to the natural rate of interest. Note that in this case the optimal response to inflation is maximised for (σ_l, κ_h), which is also our equilibrium parameter vector.

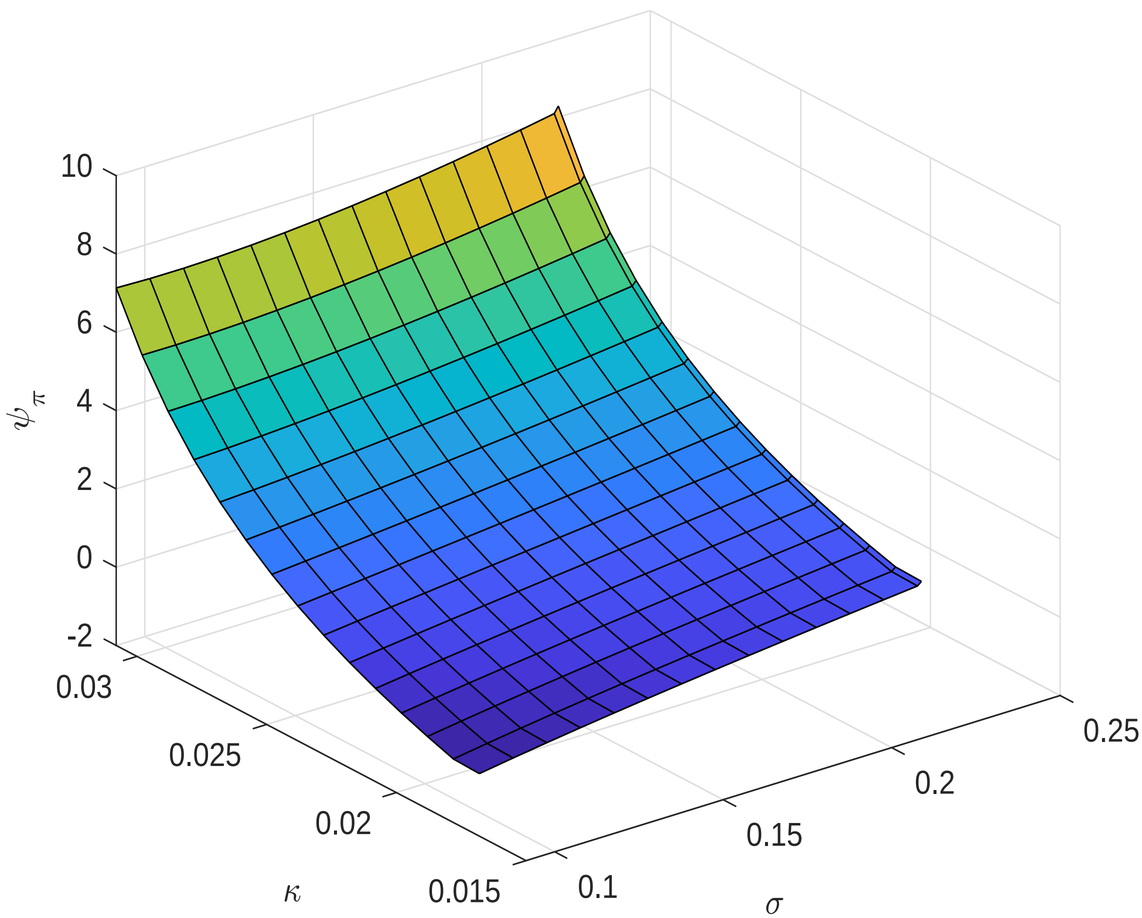

Figure 3: Optimal Taylor rule coefficient ψ_π as a function of σ and κ ($\psi_x = 0.5$ and full observation of the output gap).

In figure 5 we represent policies that implement the optimal noninertial plan for the baseline parameterization of the model and several levels of uncertainty about potential output. The solid blue line represents the optimal Taylor rules in the baseline case, that is, when the coefficients ψ_π, ψ_x are chosen in a setup where all parameters and output gap are known with certainty. The dashed-dotted brown line represents the case in which the

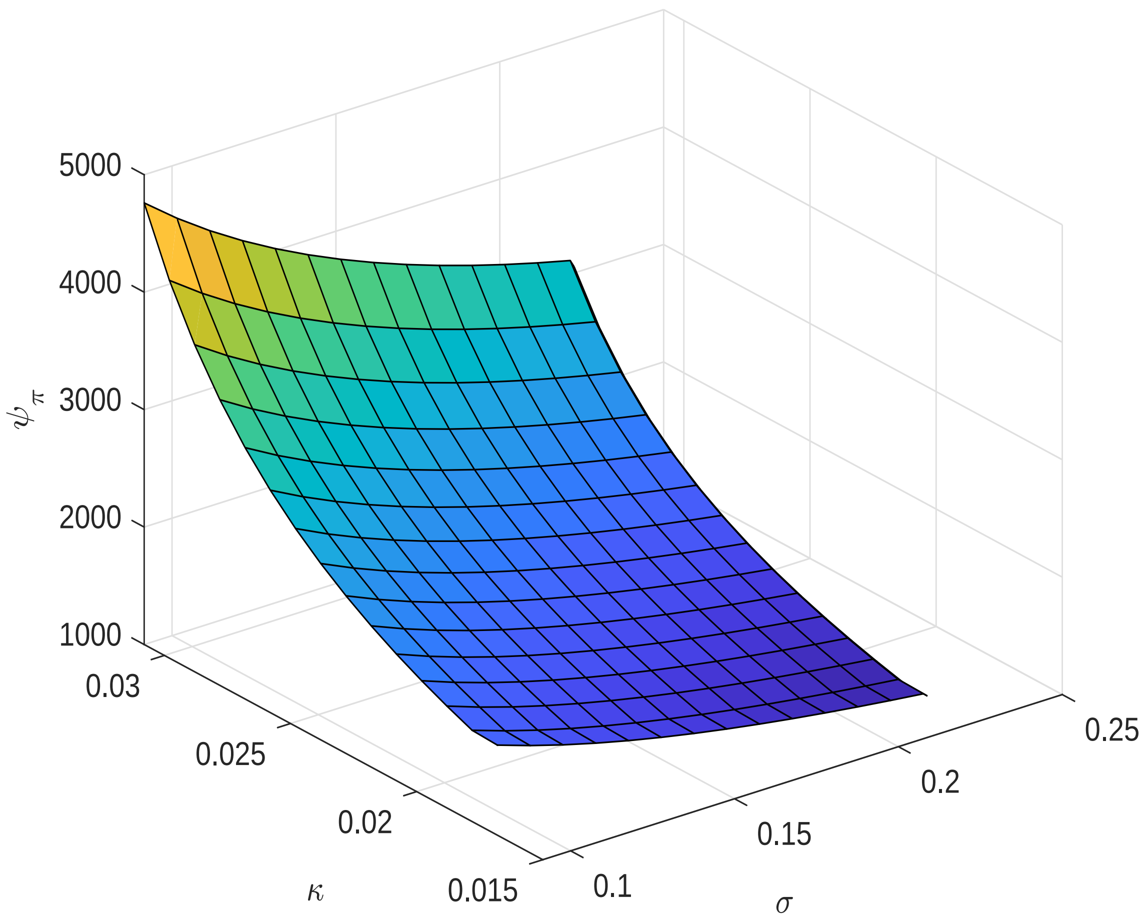

Figure 4: Optimal Taylor rule coefficient ψ_π as a function of σ and κ (for $\psi_x = 0.5$ and θ slightly above λ_x).

central bank has Knightian uncertainty about σ and κ, but output gap is observed without uncertainty. This case has been analyzed in Giannoni (2002), who shows that optimal robust policy under our calibration prescribes that the central bank reacts more strongly to shocks than under certainty. The other cases represented in the graph consider uncertainty in both parameters and potential output: each time, we reoptimise to find the optimal values of σ and κ depending on the value of θ. The white region indicates the set of policy rules that result in a determinate equilibrium for any value of uncertain parameters σ and κ, while the gray region indicates combinations of (ψ_π, ψ_x) that result in indeterminacy of the equilibrium for at least one value of the parameters.[26]

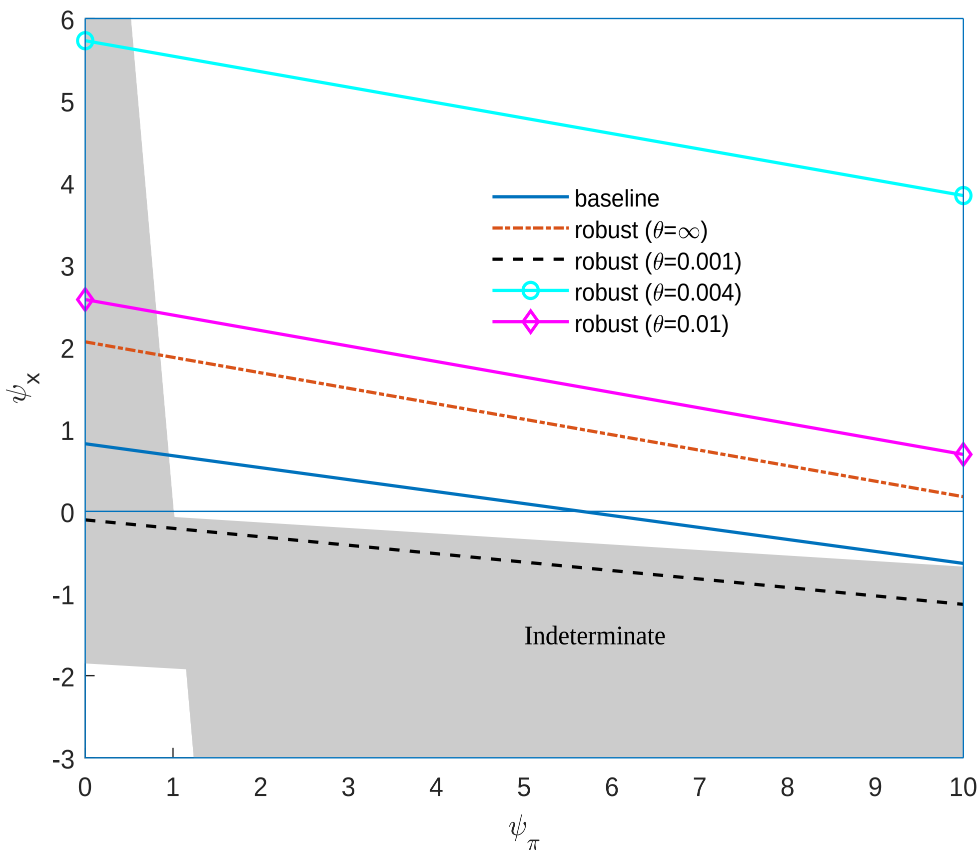

Figure 5: Robust optimal Taylor rules. The white (grey) region indicates the set of policy rules that result in a determinate (indeterminate) equilibrium for any value of uncertain parameters σ and κ. The dashed-dotted brown line is the case in Giannoni (2002).

[26]We know that, whenever $\theta > \lambda_x$, the determinacy (indeterminacy) region is the same with and without uncertainty about output gap measurement, see equation 32.

The graph shows once again that adding measurement errors in potential output to parameter uncertainty produces significant effects in terms of monetary policy response. Before discussing this, we focus on the only curve in the gray area (the dashed black line); this is the set of policy rules that obtain for the largest level of uncertainty about potential output that we pictured, which is $\theta = 0.001$. We can observe that in the range of values for ψ_π, ψ_x considered in our simulation, the equilibrium is indeterminate, even in presence of a very large response to inflation. We obtain similar results for values of $\theta < \lambda_x$, for which there is indeterminacy for at least one value of σ and κ. Therefore, for the other cases we focus on levels of uncertainty such that $\theta > \lambda_x$. Optimal robust Taylor rules with only parameter uncertainty (dashed-dotted brown line) are more aggressive than under the baseline scenario, and even more so in case of uncertainty about the potential output. In fact, the solid-circle light blue line and the solid-diamond pink line, which consider the latter dimension of uncertainty, have a higher intercept than the one with no uncertainty about potential output. Notice however that, as θ gets larger, the set of robust optimal policies tends to move closer to the dashed-dotted brown line; this squares with the evidence presented in Figure 1, which showed that, as the central bank gets more confident, the optimal robust coefficients tend to flatten towards the case with no uncertainty in potential output. In turn, the higher the latter uncertainty, the stronger the monetary policy response.

5 Concluding Remarks

Uncertainty is pervasive feature of the environment in which central banks operate. This paper analyzes the conduct of optimal discretionary robust monetary policy with two sources of uncertainty that jointly affect central bank's policymaking. The first source is a Knightian uncertainty about the intertemporal elasticity of substitution and the slope of the short-run aggregate supply curve. The second cause of uncertainty concerns the level of potential output. We show that this *double* dimension of uncertainty affects not only the magnitude of the response of the central bank to shocks, but also the transmission of the latter in terms of inflation, output and policy rate. We characterize robust monetary policy analytically under the two types of uncertainty and show that they call for a more aggressive reaction of monetary policy compared with the certainty case.

In our analysis, we exclude that the central bank could learn over time the true value of both the model parameters and of potential output. Moreover, to retain analytical tractability, we do not explore how results would change adding a cost-push shock. We leave these issues for future research.

A More on the Determination of the Structural Parameters

To determine the equilibrium value of σ and κ we differentiate the policymaker Lagrangian with respect to both parameter. Giannoni (2002) proves that, if the derivative is negative (positive), the candidate equilibrium value of the parameter is the lower (upper) bound of the interval in which it lies.

Let's start from (28). For simplicity we report it below

$$\frac{\partial \mathcal{L}_t}{\partial \sigma} = -\Theta(1-\rho)\left\{\lambda_i(1-\beta\rho)\left(\theta-\lambda_x\right)\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]\right\}$$

$$\Theta \equiv \frac{2\lambda_i\left[\theta\lambda_x\left(1-\beta\rho\right)^2+\left(\theta-\lambda_x\right)\kappa^2\right]}{\left[\left(\theta-\lambda_x\right)\left\{\kappa^2+\lambda_i\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]^2\right\}+\theta\lambda_x\left(1-\beta\rho\right)^2\right]^2}$$

As for the equilibrium processes for the endogenous variables, we must consider different parametrizations. The derivative will be negative if

1. $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\theta < \chi\lambda_x$ or $\theta > \lambda_x$;
2. $\frac{\sigma}{\kappa} < \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\chi\lambda_x < \theta < \lambda_x$ (notice that the derivative is not defined for $\theta = \Gamma\lambda_x$);

where χ and Γ are defined as in (26). Similarly, the derivative will be positive if

1. $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\chi\lambda_x \leq \theta \leq \lambda_x$;
2. $\frac{\sigma}{\kappa} < \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\theta \leq \chi\lambda_x$ or $\theta \geq \lambda_x$.

In our case, differently from Giannoni (2002), the condition $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ is not sufficient to determine a value of σ in the optimal robust equilibrium because the policymaker takes into account the effect of the misspecified output gap in the conduct of monetary policy.

By computing the derivative of the loss function with respect to κ, and considering (13)–(14) we find equation (29, which is

$$\frac{\partial \mathcal{L}_t}{\partial \kappa} = \frac{2f_x^2}{\sigma(1-\rho)(1-\beta\rho)-\rho\kappa}\left[\frac{\lambda_x\theta\rho}{\theta-\lambda_x}+\frac{\sigma\kappa(1-\rho)}{1-\beta\rho}\right] = 2f_x^2\frac{\theta\lambda_x\rho(1-\beta\rho)+\sigma\kappa\left(\theta-\lambda_x\right)(1-\rho)}{\left[\sigma(1-\rho)(1-\beta\rho)-\rho\kappa\right]\left(\theta-\lambda_x\right)(1-\beta\rho)}$$

The sign of this derivative will be determined by the following conditions:

1. if $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\theta > \lambda_x$ or $\theta < \delta_1\lambda_x$, the derivative is positive, where we have that $\delta_1 \equiv \frac{\sigma\kappa(1-\rho)}{\lambda_x(1-\beta\rho)+\sigma\kappa(1-\rho)} < 1$.

2. if $\frac{\sigma}{\kappa} < \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\delta_1\lambda_x < \theta < \lambda_x$ the derivative will be positive again.

3. If $\frac{\sigma}{\kappa} > \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\delta_1\lambda_x < \theta < \lambda_x$ the derivative is negative.

4. If $\frac{\sigma}{\kappa} < \frac{\rho}{(1-\rho)(1-\beta\rho)}$ and $\theta > \lambda_x$ or $\theta < \delta_1\lambda_x$, the loss function will be decreasing in κ.

References

Bils, Mark and Peter J Klenow, "Some evidence on the importance of sticky prices," *Journal of political economy*, 2004, *112* (5), 947–985.

Brainard, William C, "Uncertainty and the Effectiveness of Policy," *The American Economic Review*, 1967, *57* (2), 411–425.

Cukierman, Alex, "Why does the Fed smooth interest rates?," in "Monetary policy on the 75th anniversary of the federal reserve system," Springer, 1991, pp. 111–147.

_ **and Francesco Lippi**, "Endogenous monetary policy with unobserved potential output," *Journal of economic dynamics and control*, 2005, *29* (11), 1951–1983.

Ehrmann, Michael and Frank Smets, "Uncertain potential output: implications for monetary policy," *Journal of economic dynamics and control*, 2003, *27* (9), 1611–1638.

Ferrero, Giuseppe, Mario Pietrunti, and Andrea Tiseno, "Benefits of gradualism or costs of inaction? Monetary policy in times of uncertainty," *Monetary Policy in Times of*

Uncertainty (February 4, 2019). Bank of Italy Temi di Discussione (Working Paper) No, 2019, *1205.*

Giannoni, Marc P, "Does model uncertainty justify caution? Robust optimal monetary policy in a forward-looking model," *Macroeconomic Dynamics*, 2002, *6* (1), 111–144.

Gilboa, Itzhak and David Schmeidler, "Maxmin expected utility with non-unique prior," *Journal of mathematical economics*, 1989, *18* (2), 141–153.

Hansen, Lars Peter and Thomas J Sargent, *Robustness*, Princeton university press, 2008.

Leitemo, Kai and Ulf Söderström, "Robust monetary policy in a small open economy," *Journal of Economic Dynamics and Control*, 2008, *32* (10), 3218–3252.

Levin, Andrew T, Volker Wieland, and John Williams, "Robustness of simple monetary policy rules under model uncertainty," in "Monetary policy rules," University of Chicago Press, 1999, pp. 263–318.

Lippi, Francesco and Stefano Neri, "Information variables for monetary policy in an estimated structural model of the euro area," *Journal of Monetary Economics*, 2007, *54* (4), 1256–1270.

Nakamura, Emi and Jón Steinsson, "Price rigidity: Microeconomic evidence and macroeconomic implications," *Annu. Rev. Econ.*, 2013, *5* (1), 133–163.

Onatski, Alexei and James H Stock, "Robust monetary policy under model uncertainty in a small model of the US economy," *Macroeconomic Dynamics*, 2002, *6* (1), 85–110.

_ **and Noah Williams**, "Modeling model uncertainty," *Journal of the European Economic Association*, 2003, *1* (5), 1087–1122.

Orphanides, Athanasios, "Monetary policy rules based on real-time data," *American Economic Review*, 2001, *91* (4), 964–985.

_ , "Monetary policy evaluation with noisy information," *Journal of Monetary economics*, 2003, *50* (3), 605–631.

_ , "The quest for prosperity without inflation," *Journal of monetary Economics*, 2003, *50* (3), 633–663.

Sack, Brian, "Does the Fed act gradually? A VAR analysis," *Journal of Monetary Economics*, 2000, *46* (1), 229–256.

_ **and Volker Wieland**, "Interest-rate smoothing and optimal monetary policy: a review of recent empirical evidence," *Journal of Economics and Business*, 2000, *52* (1-2), 205–228.

Söderström, Ulf, "Monetary policy with uncertain parameters," *Scandinavian Journal of Economics*, 2002, *104* (1), 125–145.

Svensson, Lars EO and Michael Woodford, "Indicator variables for optimal policy under asymmetric information," *Journal of Economic Dynamics and Control*, 2004, *28* (4), 661–690.

Tillmann, Peter, "Robust monetary policy, optimal delegation and misspecified potential output," *Economics Letters*, 2014, *123* (2), 244–247.

Woodford, Michael, "Optimal monetary policy inertia," *The Manchester School*, 1999, *67*, 1–35.

_ , *Interest and prices: Foundations of a theory of monetary policy*, princeton university press, 2011.

RECENTLY PUBLISHED "TEMI" (*)

N. 1314 – *Working horizon and labour supply: the effect of raising the full retirement age on middle-aged individuals*, by Francesca Carta and Marta De Philippis (February 2021).

N. 1315 – *Bank credit and market-based finance for corporations: the effects of minibond issuances*, by Steven Ongena, Sara Pinoli, Paola Rossi and Alessandro Scopelliti (February 2021).

N. 1316 – *Is inflation targeting a strategy past its sell-by date?*, by Alberto Locarno and Alessandra Locarno (February 2021).

N. 1317 – *Declining natural interest rate in the US: the pension system matters*, by Jacopo Bonchi and Giacomo Caracciolo (February 2021).

N. 1318 – *Can we measure inflation expectations using Twitter?*, by Cristina Angelico, Juri Marcucci, Marcello Miccoli and Filippo Quarta (February 2021).

N. 1319 – *Identifying deposits' outflows in real-time*, by Edoardo Rainone (February 2021).

N. 1320 – *Whatever it takes to save the planet? Central banks and unconventional green policy*, by Alessandro Ferrari and Valerio Nispi Landi (February 2021).

N. 1321 – *The power of text-based indicators in forecasting the Italian economic activity*, by Valentina Aprigliano, Simone Emiliozzi, Gabriele Guaitoli, Andrea Luciani, Juri Marcucci and Libero Monteforte (March 2021).

N. 1322 – *Judicial efficiency and bank credit to firms*, by Giacomo Rodano (March 2021).

N. 1323 – *Unconventional monetary policies and expectations on economic variables*, by Alessio Anzuini and Luca Rossi (March 2021).

N. 1324 – *Modeling and forecasting macroeconomic dowside risk*, by Davide Delle Monache, Andrea De Polis and Ivan Petrella (March 2021).

N. 1325 – *Foreclosures and house prices*, by Michele Loberto (March 2021).

N. 1326 – *inancial structure and bank relationships of Italian multinational firms*, by Raffaello Bronzini, Alessio D'Ignazio and Davide Revelli (March 2021).

N. 1327 – *Foreign investors and target firms' financial structure: cavalry or lucusts?*, by Lorenzo Bencivelli and Beniamino Pisicoli (April 2021).

N. 1328 – *Board composition and performance of state-owned enterprises: quasi experimental evidence*, by Audinga Baltrunaite, Mario Cannella, Sauro Mocetti and Giacomo Roma (April 2021).

N. 1329 – *Can internet banking affect households' participation in financial markets and financial awareness?*, by Valentina Michelangeli and Eliana Viviano (April 2021).

N. 1330 – *(In)Efficient separations, firing costs and temporary contracts*, by Andrea Gerali, Elisa Guglielminetti and Danilo Liberati (April 2021).

N. 1331 – *The catalytic role of IMF programs*, by Claudia Maurini and Alessandro Schiavone (April 2021).

N. 1332 – *Dating the euro area business cycle: an evaluation*, by Claudia Pacella (April 2021).

N. 1333 – *Population aging, relative prices and capital flows across the globe*, by Andrea Papetti (April 2021).

N. 1334 – *What drives investors to chase returns?*, by Jonathan Huntley, Valentina Michelangeli and Felix Reichling (April 2021).

N. 1335 – *Managerial talent and managerial practices: are they complements?*, by Audinga Baltrunaite, Giulia Bovini and Sauro Mocetti (April 2021).

(*) Requests for copies should be sent to:
Banca d'Italia – Servizio Studi di struttura economica e finanziaria – Divisione Biblioteca e Archivio storico – Via Nazionale, 91 – 00184 Rome – (fax 0039 06 47922059). They are available on the Internet www.bancaditalia.it.

2019

ALBANESE G., M. CIOFFI and P. TOMMASINO, *Legislators' behaviour and electoral rules: evidence from an Italian reform,* European Journal of Political Economy, v. 59, pp. 423-444, **WP 1135 (September 2017).**

APRIGLIANO V., G. ARDIZZI and L. MONTEFORTE, *Using the payment system data to forecast the economic activity,* International Journal of Central Banking, v. 15, 4, pp. 55-80, **WP 1098 (February 2017).**

ARNAUDO D., G. MICUCCI, M. RIGON and P. ROSSI, *Should I stay or should I go? Firms' mobility across banks in the aftermath of the financial crisis,* Italian Economic Journal / Rivista italiana degli economisti, v. 5, 1, pp. 17-37, **WP 1086 (October 2016).**

BASSO G., F. D'AMURI and G. PERI, *Immigrants, labor market dynamics and adjustment to shocks in the euro area,* IMF Economic Review, v. 67, 3, pp. 528-572, **WP 1195 (November 2018).**

BATINI N., G. MELINA and S. VILLA, *Fiscal buffers, private debt, and recession: the good, the bad and the ugly,* Journal of Macroeconomics, v. 62, **WP 1186 (July 2018).**

BURLON L., A. NOTARPIETRO and M. PISANI, *Macroeconomic effects of an open-ended asset purchase programme,* Journal of Policy Modeling, v. 41, 6, pp. 1144-1159, **WP 1185 (July 2018).**

BUSETTI F. and M. CAIVANO, *Low frequency drivers of the real interest rate: empirical evidence for advanced economies,* International Finance, v. 22, 2, pp. 171-185, **WP 1132 (September 2017).**

CAPPELLETTI G., G. GUAZZAROTTI and P. TOMMASINO, *Tax deferral and mutual fund inflows: evidence from a quasi-natural experiment,* Fiscal Studies, v. 40, 2, pp. 211-237, **WP 938 (November 2013).**

CARDANI R., A. PACCAGNINI and S. VILLA, *Forecasting with instabilities: an application to DSGE models with financial frictions,* Journal of Macroeconomics, v. 61, **WP 1234 (September 2019).**

CHIADES P., L. GRECO, V. MENGOTTO, L. MORETTI and P. VALBONESI, *Fiscal consolidation by intergovernmental transfers cuts? The unpleasant effect on expenditure arrears,* Economic Modelling, v. 77, pp. 266-275, **WP 1076 (July 2016).**

CIANI E., F. DAVID and G. DE BLASIO, *Local responses to labor demand shocks: a re-assessment of the case of Italy,* Regional Science and Urban Economics, v. 75, pp. 1-21, **WP 1112 (April 2017).**

CIANI E. and P. FISHER, *Dif-in-dif estimators of multiplicative treatment effects,* Journal of Econometric Methods, v. 8. 1, pp. 1-10, **WP 985 (November 2014).**

CIAPANNA E. and M. TABOGA, *Bayesian analysis of coefficient instability in dynamic regressions,* Econometrics, MDPI, Open Access Journal, v. 7, 3, pp.1-32, **WP 836 (November 2011).**

COLETTA M., R. DE BONIS and S. PIERMATTEI, *Household debt in OECD countries: the role of supply-side and demand-side factors,* Social Indicators Research, v. 143, 3, pp. 1185–1217, **WP 989 (November 2014).**

COVA P., P. PAGANO and M. PISANI, *Domestic and international effects of the Eurosystem Expanded Asset Purchase Programme,* IMF Economic Review, v. 67, 2, pp. 315-348, **WP 1036 (October 2015).**

ERCOLANI V. and J. VALLE E AZEVEDO, *How can the government spending multiplier be small at the zero lower bound?,* Macroeconomic Dynamics, v. 23, 8. pp. 3457-2482, **WP 1174 (April 2018).**

FERRERO G., M. GROSS and S. NERI, *On secular stagnation and low interest rates: demography matters,* International Finance, v. 22, 3, pp. 262-278, **WP 1137 (September 2017).**

FOA G., L. GAMBACORTA, L. GUISO and P. E. MISTRULLI, *The supply side of household finance,* Review of Financial Studies, v.32, 10, pp. 3762-3798, **WP 1044 (November 2015).**

GERALI A. and S. NERI, *Natural rates across the Atlantic,* Journal of Macroeconomics, v. 62, article 103019, **WP 1140 (September 2017).**

GIORDANO C., M. MARINUCCI and A. SILVESTRINI, *The macro determinants of firms' and households' investment: evidence from Italy,* Economic Modelling, v. 78, pp. 118-133, **WP 1167 (March 2018).**

GOMELLINI M., D. PELLEGRINO and F. GIFFONI, *Human capital and urban growth in Italy,1981-2001,* Review of Urban & Regional Development Studies, v. 31, 2, pp. 77-101, **WP 1127 (July 2017).**

LIBERATI D. and M. LOBERTO, *Taxation and housing markets with search frictions,* Journal of Housing Economics, v. 46, article 101632, **WP 1105 (March 2017).**

MAGRI S., *Are lenders using risk-based pricing in the Italian consumer loan market? The effect of the 2008 crisis,* Journal of Credit Risk, v. 15, 1, pp. 27-65, **WP 1164 (January 2018).**

MERCATANTI A., T. MAKINEN and A. SILVESTRINI, *The role of financial factors for european corporate investment,* Journal of International Money and Finance, v. 96, pp. 246-258, **WP 1148 (October 2017).**

MIGLIETTA A., C. PICILLO and M. PIETRUNTI, *The impact of margin policies on the Italian repo market,* The North American Journal of Economics and Finance, v. 50, **WP 1028 (October 2015).**

MONTEFORTE L. and V. RAPONI, *Short-term forecasts of economic activity: are fortnightly factors useful?,* Journal of Forecasting, v. 38, 3, pp. 207-221, **WP 1177 (June 2018).**

NERI S. and A. NOTARPIETRO, *Collateral constraints, the zero lower bound, and the debt–deflation mechanism,* Economics Letters, v. 174, pp. 144-148, **WP 1040 (November 2015).**

PANCRAZI R. and M. PIETRUNTI, *Natural expectations and home equity extraction,* Journal of Housing Economics, v. 46, 4, **WP 984 (November 2014).**

PEREDA FERNANDEZ S., *Teachers and cheaters. Just an anagram?*, Journal of Human Capital, v. 13, 4, pp. 635-669, **WP 1047 (January 2016).**

RIGGI M., *Capital destruction, jobless recoveries, and the discipline device role of unemployment,* Macroeconomic Dynamics, v. 23, 2, pp. 590-624, **WP 871 (July 2012).**

2020

ALESSANDRI P. and M. BOTTERO, *Bank lending in uncertain times,* R European Economic Review, V. 128, **WP 1109 (April 2017).**

ANTUNES A. and V. ERCOLANI, *Public debt expansions and the dynamics of the household borrowing constraint,* Review of Economic Dynamics, v. 37, pp. 1-32, **WP 1268 (March 2020).**

ARDUINI T., E. PATACCHINI and E. RAINONE, *Treatment effects with heterogeneous externalities,* Journal of Business & Economic Statistics, , v. 38, 4, pp. 826-838, **WP 974 (October 2014).**

BOLOGNA P., A. MIGLIETTA and A. SEGURA, *Contagion in the CoCos market? A case study of two stress events,* International Journal of Central Banking, v. 16, 6, pp. 137-184, **WP 1201 (November 2018).**

BOTTERO M., F. MEZZANOTTI and S. LENZU, *Sovereign debt exposure and the Bank Lending Channel: impact on credit supply and the real economy,* Journal of International Economics, v. 126, article 103328, **WP 1032 (October 2015).**

BRIPI F., D. LOSCHIAVO and D. REVELLI, *Services trade and credit frictions: evidence with matched bank – firm data,* The World Economy, v. 43, 5, pp. 1216-1252, **WP 1110 (April 2017).**

BRONZINI R., G. CARAMELLINO and S. MAGRI, *Venture capitalists at work: a Diff-in-Diff approach at late-stages of the screening process,* Journal of Business Venturing, v. 35, 3, **WP 1131 (September 2017).**

BRONZINI R., S. MOCETTI and M. MONGARDINI, *The economic effects of big events: evidence from the Great Jubilee 2000 in Rome,* Journal of Regional Science, v. 60, 4, pp. 801-822, **WP 1208 (February 2019).**

COIBION O., Y. GORODNICHENKO and T. ROPELE, *Inflation expectations and firms' decisions: new causal evidence,* Quarterly Journal of Economics, v. 135, 1, pp. 165-219, **WP 1219 (April 2019).**

CORSELLO F. and V. NISPI LANDI, *Labor market and financial shocks: a time-varying analysis,* Journal of Money, Credit and Banking, v. 52, 4, pp. 777-801, **WP 1179 (June 2018).**

COVA P. and F. NATOLI, *The risk-taking channel of international financial flows,* Journal of International Money and Finance, v. 102, **WP 1152 (December 2017).**

D'ALESSIO G., *Measurement errors in survey data and the estimation of poverty and inequality indices,* Statistica Applicata - Italian Journal of Applied Statistics, v. 32, 3, **WP 1116 (June 2017).**

DEL PRETE S. and S. FEDERICO, *Do links between banks matter for bilateral trade? Evidence from financial crises,* Review of World Economic, v. 156, 4, pp. 859 - 885, **WP 1217 (April 2019).**

D'IGNAZIO A. and C. MENON, *The causal effect of credit Guarantees for SMEs: evidence from Italy,* The Scandinavian Journal of Economics, v. 122, 1, pp. 191-218, **WP 900 (February 2013).**

ERCOLANI V. and F. NATOLI, *Forecasting US recessions: the role of economic uncertainty,* Economics Letters, v. 193, **WP 1299 (October 2020).**

MAKINEN T., L. SARNO and G. ZINNA, *Risky bank guarantees,* Journal of Financial Economics, v. 136, 2, pp. 490-522, **WP 1232 (July 2019).**

MODENA F., E. RETTORE and G. M. TANZI, *The effect of grants on university dropout rates: evidence from the Italian case,* Journal of Human Capital, v. 14, 3, pp. 343-370, **WP 1193 (September 2018).**

NISPI LANDI V., *Capital controls spillovers,* Journal of International Money and Finance, v. 109, **WP 1184 (July 2018).**

PERICOLI M., *On risk factors of the stock–bond correlation,* International Finance, v. 23, 3, pp. 392-416, **WP 1198 (November 2018).**

RAINONE E., *The network nature of OTC interest rates,* Journal of Financial Markets, v.47, article 100525, **WP 1022 (July 2015).**

RAINONE E. and F. VACIRCA, *Estimating the money market microstructure with negative and zero interest rates,* Quantitative Finance, v. 20, 2, pp. 207-234, **WP 1059 (March 2016).**

RIZZICA L., *Raising aspirations and higher education. Evidence from the UK's widening participation policy,* Journal of Labor Economics, v. 38, 1, pp. 183-214, **WP 1188 (September 2018).**

SANTIONI, R., F. SCHIANTARELLI and P. STRAHAN, *Internal capital markets in times of crisis: the benefit of group affiliation*, Review of Finance, v. 24, 4, pp. 773-811, **WP 1146 (October 2017).**

SCHIANTARELLI F., M. STACCHINI and P. STRAHAN, *Bank Quality, judicial efficiency and loan repayment delays in Italy,* Journal of Finance , v. 75, 4, pp. 2139-2178, **WP 1072 (July 2016).**

2021

ALBANESE G., E. CIANI and G. DE BLASIO, *Anything new in town? The local effects of urban regeneration policies in Italy,* Regional Science and Urban Economics, v. 86, **WP 1214 (April 2019).**

FIDORA M., C. GIORDANO and M. SCHMITZ, *Real exchange rate misalignments in the Euro Area,* Open Economies Review, v. 32, 1, pp. 71-107, **WP 1162 (January 2018).**

LI F., A. MERCATANTI, T. MAKINEN and A. SILVESTRINI, *A regression discontinuity design for ordinal running variables: evaluating central bank purchases of corporate bonds,* The Annals of Applied Statistics, v. 15, 1, pp. 304-322, **WP 1213 (March 2019).**

LOSCHIAVO D., *Household debt and income inequality: evidence from Italian survey data,* Review of Income and Wealth. v. 67, 1, pp. 61-103, **WP 1095 (January 2017).**

NISPI LANDI V. and A. SCHIAVONE, *The effectiveness of capital controls,* Open Economies Review, v. 32, 1, pp. 183-211, **WP 1200 (November 2018).**

PEREDA FERNANDEZ S., *Copula-based random effects models for clustered data,* Journal of Business & Economic Statistics, v. 39, 2, pp. 575-588, **WP 1092 (January 2017).**

FORTHCOMING

ACCETTURO A., A. LAMORGESE, S. MOCETTI and D. PELLEGRINO, *Housing Price elasticity and growth: evidence from Italian cities,* Journal of Economic Geography, **WP 1267 (March 2020).**

ALBANESE G., G. DE BLASIO and A. LOCATELLI, *Does EU regional policy promote local TFP growth? Evidence from the Italian Mezzogiorno,* Papers in Regional Science, **WP 1253 (December 2019).**

ANZUINI A. and L. ROSSI, *Fiscal policy in the US: a new measure of uncertainty and its effects on the American economy*, Empirical Economics, **WP 1197 (November 2018).**

APRIGLIANO V. and D. LIBERATI, *Using credit variables to date business cycle and to estimate the probabilities of recession in real time*, The Manchester School, **WP 1229 (July 2019).**

BALTRUNAITE A., C. GIORGIANTONIO, S. MOCETTI and T. ORLANDO, Discretion and supplier selection in public procurement, Journal of Law, Economics, and Organization, **WP 1178 (June 2018)**

COVA P., P. PAGANO, A. NOTARPIETRO and M. PISANI, *Secular stagnation, R&D, public investment and monetary policy: a global-model perspective,* Macroeconomic Dynamics, **WP 1156 (December 2017).**

DE PHILIPPIS M., *Multitask agents and incentives: the case of teaching and research for university professors,* Economic Journal, **WP 1042 (December 2015).**

DEL PRETE S. and M. L. STEFANI, *Women as "Gold Dust": gender diversity in top boards and the performance of Italian banks,* Economic Notes, Monte dei Paschi di Siena, **WP 1014 (June 2015).**

HERTWECK M., V. LEWIS and S. VILLA, *Going the extra mile: effort by workers and job-seekers,* Journal of Money, Credit and Banking, **WP 1277 (June 2020).**

METELLI L. and F. NATOLI, *The international transmission of US tax shocks: a proxy-SVAR approach,* IMF Economic Review, **WP 1223 (June 2019).**

MOCETTI S., G. ROMA and E. RUBOLINO, *Knocking on parents' doors: regulation and intergenerational mobility,* Journal of Human Resources, **WP 1182 (July 2018).**

PERICOLI M. and M. TABOGA, *Nearly exact Bayesian estimation of non-linear no-arbitrage term-structure models,* Journal of Financial Econometrics, **WP 1189 (September 2018).**