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Evaluating the macroeconomic effects of the ECB's unconventional monetary policies

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Abstract

We quantify the macroeconomic effects of the European Central Bank's unconventional monetary policies using a DSGE model which includes a set of shadow interest rates. Extracted from the yield curve, these shadow rates provide unconstrained measures of the overall stance of monetary policy. Counterfactual analyses show that, without unconventional measures, the euro area would have suffered (i) a substantial loss of output since the Great Recession and (ii) a period of deflation from mid-2015 to early 2017. Specifically, year-on-year inflation and GDP growth would have been on average about 0.61% and 1.09% below their actual levels over the period 2014Q1-2017Q2, respectively.

Keywords: Unconventional monetary policy, shadow policy rate, DSGE model, euro area

JEL classification: E32 ; E44 ; E52

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Non-Technical Summary

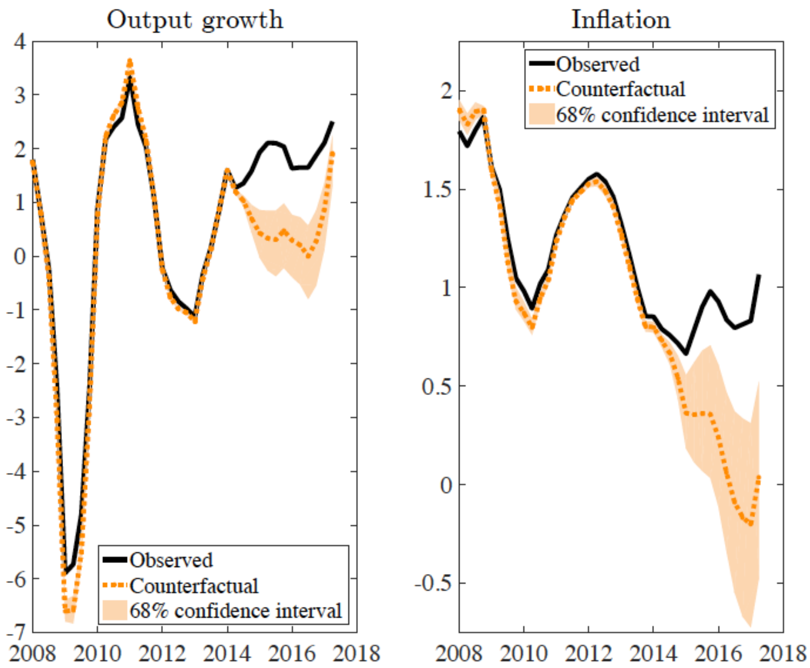
Decisions of central banks rely on an assessment of their monetary policy stance, i.e. the contribution made by monetary policy to real economic and financial developments. In the past, policymakers could compare the policy rate to the prescriptions of simple policy rules, to get a sense of whether their actions were appropriate in view of their objectives. However, the severity of the financial crisis in 2008 led many central banks to lower their key rates at levels close to their effective lower bound (ELB), limiting their ability to stimulate further the economy. Unable to move the short-end of the yield curve, central banks turned to a number of unconventional policies to provide additional monetary accommodation. In the context of the euro area, these policies included an increase in the average maturity of outstanding liquidity, the use of forward guidance, several asset purchase programs and negative deposit facility rates. With the implementation of such measures, there is no directly observable indicator that summarizes the stance of policy. How can one quantify the effects of these new policy measures from a macroeconomic perspective?

In this paper, we address this question by integrating a set of shadow policy rates in a dynamic stochastic general equilibrium (DSGE) model to reveal the macroeconomic effects of unconventional measures implemented by the European Central Bank (ECB). The shadow rate is the shortest maturity rate, extracted from a term structure model, that would generate the observed yield curve had the ELB not been binding. It incorporates both the effect of monetary policy measures on current economic conditions as well as market expectations of future policy actions. The shadow rate coincides with the policy rate in normal times and is free to go into negative territory when the policy rate is stuck at its lower bound. Particularly, exploiting the entire yield curve allows to account for the influence of direct and/or indirect market interventions on intermediate and longer maturity rates. It can therefore be used as a convenient indicator for measuring the total accommodation provided by both conventional and unconventional policies.

Therefore, we propose to compare a Taylor rule based on the common component extracted from a set of shadow rates with the Eonia rate. Taking the common component allows us to address the uncertainty surrounding the measurement of shadow rates. The resulting shadow rate is then used to extract the shocks stemming from all monetary policy actions within our DSGE model. Through a counterfactual exercise, these shocks can subsequently be replaced by shocks that would have kept the shadow rate at the Eonia rate level, i.e the rate that represents the conventional part of monetary policy. This analysis enables us to isolate and gauge the effects of unconventional policies on economic activity and inflation.

We find that in the absence of such monetary policies, the euro area would have suffered a quarterly output loss of about 4.5% in 2017Q2. Moreover, these measures helped in avoiding a period of deflation from mid-2015 to early 2017. This translates into year-on-year (y-o-y) inflation and GDP growth differentials of 0.26% and 0.51% on average over the period 2008Q1-2017Q2, respectively. Drawing attention on the period 2014Q1-2017Q2, when public and private sector asset purchase programs have been announced and conducted, y-o-y inflation and GDP growth would have been lower by 0.61% and 1.09%, respectively (see figure below). Our approach has the advantage of overcoming the computational issues associated with the presence of the ELB by using traditional estimation techniques.

Year-on-year euro area output growth and inflation rates (percent)



Note: Confidence intervals are built using 10 000 draws from the posterior distribution of the structural parameters.

Evaluation des effets macroéconomiques des mesures non conventionnelles de la BCE

RÉSUMÉ

Nous quantifions les effets macroéconomiques des politiques monétaires non conventionnelles de la Banque Centrale Européenne, à l'aide d'un modèle DSGE comprenant un ensemble de taux d'intérêt virtuels (shadow rate). Extraits de la courbe des taux, ces taux virtuels fournissent des mesures non contraintes de l'orientation générale de la politique monétaire. Nos analyses contrefactuelles montrent que, sans ces mesures non conventionnelles, la zone euro aurait subi (i) une perte de production substantielle depuis la Grande Récession et (ii) une période de déflation allant de la mi-2015 au début 2017. Le glissement annuel de l'inflation aurait été en moyenne 0,61% en dessous de son niveau observé et celui de la croissance du PIB plus bas de 1,09%, au cours de la période 2014T1-2017T2.

Mots-clés : politique monétaire non conventionnelle, taux d'intérêt virtuel, modèle DSGE, zone euro.

1. Introduction

Decisions of central banks rely on an assessment of their monetary policy stance, i.e. the contribution made by monetary policy to real economic and financial developments. In the past, policymakers could compare the policy rate to the prescriptions of simple policy rules, to get a sense of whether their actions were appropriate in view of their objectives. However, the severity of the financial crisis in 2008 led many central banks to lower their key rates at levels close to their effective lower bound (ELB), limiting their ability to stimulate further the economy. Unable to move the short-end of the yield curve, central banks turned to a number of unconventional policies to provide additional monetary accommodation. In the context of the euro area, these policies included an increase in the average maturity of outstanding liquidity, the use of forward guidance, several asset purchase programs and negative deposit facility rates. With the implementation of such measures, there is no directly observable indicator that summarizes the stance of policy. How can one quantify the effects of these new policy measures from a macroeconomic perspective?

In this paper, we address this question by integrating a set of *shadow policy rates* in a dynamic stochastic general equilibrium (DSGE) model to reveal the macroeconomic effects of unconventional measures implemented by the European Central Bank (ECB).

The shadow rate is the shortest maturity rate, extracted from a term structure model, that would generate the observed yield curve had the ELB not been binding (Kim and Singleton, 2012; Krippner, 2012; Christensen and Rudebusch, 2015, 2016). It incorporates both the effect of monetary policy measures on current economic conditions as well as market expectations of future policy actions. The shadow rate coincides with the policy rate in normal times and is free to go into negative territory when the policy rate is stuck at its lower bound. Claus, Claus and Krippner (2014), Francis, Jackson and Owyang (2014) and Van Zandweghe (2015) show that the shadow rate captures the stance of monetary policy during lower bound episodes in the same way the policy rate does in normal times. Hence, the dynamic relationships between macroeconomic variables and monetary policy are preserved, in any economic environment, by using a shadow rate. Particularly, exploiting the entire yield curve allows to account for the influence of direct and/or indirect market interventions on intermediate and longer maturity rates. It can therefore be used as a convenient indicator for measuring the total accommodation provided by both conventional and unconventional policies (Krippner, 2013; Wu and Xia, 2016).

In order to adequately quantify the macroeconomic effects of unconventional policies, we further need a macroeconomic model that is structural in the sense that: *(i)* it formalizes the behavior of economic agents on the basis of explicit micro-foundations and *(ii)* it can appropriately control for the effects of policy measures through expectations to respond to the Lucas (1976) critique. Hence, we consider a medium-scale DSGE model *à la* Smets and Wouters (2007), as it has been successful in providing an empirically plausible account of key macroeconomic variables (see also Christiano et al., 2017, for a discussion on the importance of DSGE models in the policy process). We deliberately choose to keep such a standard framework because: *(i)* it is challenging to incorporate all the channels through which we think unconventional measures can act (selecting only a few of these channels could distort the results) and *(ii)* introducing a shadow rate in a model has the advantage of bypassing the non-linearity stemming from the existence of the lower bound. In addition, Wu and Zhang (2017) theoretically show that the impact of unconventional measures (particularly asset purchases and lending facilities) is identical to that of a negative shadow rate that enters directly into the IS curve, validating our approach.

Therefore, we propose to compare a Taylor rule based on the common component extracted from a *set* of shadow rates with the Eonia rate. Taking the common component allows us to address the uncertainty surrounding the measurement of shadow rates. The resulting shadow rate is then used to extract the shocks stemming from all monetary policy actions within our DSGE model. Through a counterfactual exercise, these shocks can subsequently be replaced by shocks that would have kept the shadow rate at the Eonia rate level, i.e the rate that represents the conventional part of monetary policy. This analysis enables us to isolate and gauge the effects of unconventional policies on economic activity and inflation.

We find that in the absence of such monetary policies, the euro area would have suffered a quarterly output loss of about 4.5% in 2017Q2. Moreover, these measures helped in avoiding a period of deflation from mid-2015 to early 2017. This translates into year-on-year (y-o-y) inflation and GDP growth differentials of 0.26% and 0.51% on average over the period 2008Q1-2017Q2, respectively. Drawing attention on the period 2014Q1-2017Q2, when public and private sector asset purchase programs have been announced and conducted, y-o-y inflation and GDP growth would have been lower by 0.61% and 1.09%, respectively. Our analysis also highlights that we can still use standard linear DSGE models in low interest rate environments when using an unconstrained proxy of the monetary policy stance such as the shadow rate.

Despite the growing interest in unconventional monetary policies, the literature has mainly concentrated on the effects of FOMC-decisions on financial markets, especially through event studies (see the survey by Bhattarai and Neely, 2016). There are relatively few studies that investigate the impact of unconventional monetary policies on macro variables, whether for the United States or the euro area.[1]

[1]These studies include Chen, Cúrdia and Ferrero (2012), Baumeister and Benati (2013), Gertler and Karadi (2013), Cova, Pagano and Pisani (2015), Andrade, Breckenfelder, De Fiore, Karadi and Tristani (2016), Sahuc (2016) and Weale and Wieladek (2016) on asset purchases, Del Negro, Eggertsson, Ferrero and Kiyotaki (2017) and Cahn, Matheron and Sahuc (2017) on liquidity injections, and Del Negro, Giannoni and Patterson (2015), McKay, Nakamura and Steinsson (2016), Sahuc (2016) and Kulish, Morley and Robinson (2017) on forward guidance.

In addition, these studies focus exclusively on the effects of a subset of unconventional monetary measures (i.e. they study asset purchases, liquidity injections, or forward guidance in isolation), with the notable exceptions of Engen, Laubach and Reifschneider (2015) and Wu and Xia (2016). The former evaluate the macroeconomic effects of both forward guidance and asset purchases in the United States by including private-sector forecasters' perceptions of monetary policy in a DSGE model. Nonetheless, survey data are not available at a sufficiently high frequency making the stance of monetary policy harder to gauge in real time. The latter assess the effects of the various measures adopted by the Fed after the Great Recession using their estimate of the shadow rate in a factor-augmented Vector Autoregression (VAR). However, VAR-based policy counterfactuals are sensitive to *(i)* unknown structural characteristics of the underlying data generating process and *(ii)* identification schemes (Benati, 2010). Note that the VAR model by Wu and Xia (2016) displays a price puzzle (i.e. aggregate prices and the interest rate move in the same direction following a monetary policy shock) that can cause difficulties in interpretation when considering counterfactual monetary policy regimes.

Our paper is the first to introduce shadow rates within a consistent DSGE framework to provide a tractable assessment of the macroeconomic effects of *all* unconventional policies implemented by a central bank since 2008. Our approach has the advantage of overcoming the computational issues associated with the presence of the ELB by using traditional estimation techniques.

In the remainder of the paper Section 2 introduces shadow policy rates for the euro area, Section 3 describes the dynamic stochastic general equilibrium model and its estimation, Section 4 presents our empirical results on the quantification of the effects of unconventional monetary policy measures in the euro area, and Section 5 concludes.

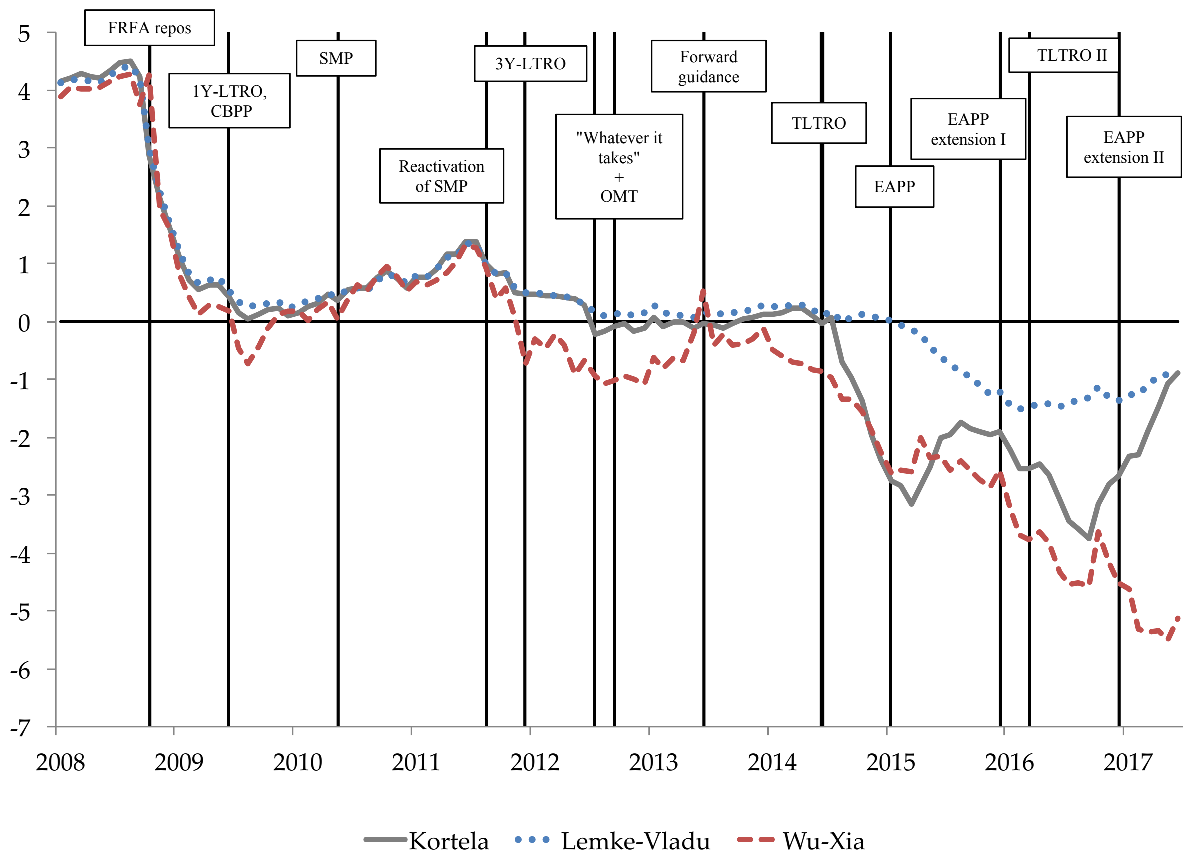
2. Shadow Interest Rates and Monetary Policy

Shadow rates have become increasingly popular in summarizing the stance of monetary policy due to their maintained correlation with macroeconomic variables, even when key policy rates are kept at the ELB (see, Krippner, 2013; Hakkio and Kahn, 2014; Doh and Choi, 2016; Wu and Xia, 2016). This desirable property comes from the fact that shadow rates typically stem from term structure models which exploit the entire yield curve, including long-term yields which are highly informative on expectations of future short-term yields. Particularly, the shadow rate is the shortest maturity rate, extracted from a term structure model, that would generate the observed yield curve had the ELB not been binding (Kim and Singleton, 2012; Krippner, 2012; Christensen and Rudebusch, 2015, 2016).[2] The shadow rate coincides with the policy rate in normal times and is free to go into negative

[2]Shadow-rate term structure models account for the ELB by setting the policy rate R_t, which is used for discounting cash flows when valuing securities, equal to the lower bound $\underline{b}_t$ or the shadow rate S_t, whichever is larger: $R_t = \max(\underline{b}_t, S_t)$. Therefore, within the confines of shadow-rate term structure models, the shadow rate S_t is (by construction) the short-rate that explains the yield curve in a fictitious world where the ELB is not binding. This is also why the shadow rate S_t coincindes with the policy rate R_t in periods when the ELB is not binding.

territory when the policy rate is stuck at its lower bound. Specifically, exploiting the entire yield curve allows to account for the influence of direct and/or indirect market interventions on intermediate and longer maturity rates. Therefore, it incorporates both the effect of monetary policy measures on current economic conditions as well as market expectations of future policy actions.The shadow policy rate can then be easily plugged into existing quantitative models for monetary policy analysis.

Figure 1. Monetary policy measures in the euro area and alternative shadow rates



Note: The black vertical lines represent, respectively, the announcements of the main monetary policy measures implemented in the euro area: October 2008 (FRFA repos), June 2009 (1Y-LTRO and CBPP), May 2010 (SMP), August 2011 (Reactivation of SMP), December 2011 (3Y-LTRO), July 2012 ("Whatever it takes"), September 2012 (OMT), June 2013 (Forward guidance), June 2014 (TLTRO), January 2015 (EAPP), December 2015 (EAPP extension I), March 2016 (TLTRO II) and December 2016 (EAPP extension II).

The main advantage of using a shadow rate to gauge the overall monetary policy stance is that it preserves continuity and consistency. First, Claus, Claus and Krippner (2014), Francis, Jackson and Owyang (2014) and Van Zandweghe (2015) show that the shadow rate captures the stance of monetary policy during lower bound episodes in the same way the policy rate does in normal times. Hence, the dynamic relationships between macroeconomic variables and monetary policy are preserved, in any economic environment, by using a shadow rate. Claus, Claus and Krippner (2014) find that the shadow rate is a reasonable approximation of both conventional and unconventional monetary policy shocks in the US. Since the Federal Reserve began to use unconventional methods, the impact of monetary policy surprises on asset markets is estimated to have been larger compared to the prior conventional period. Francis, Jackson and Owyang (2014) find that, when using a dataset that spans both the pre-ZLB and ZLB periods in the US, the shadow rate acts as a fairly good proxy for monetary policy by producing impulse responses of macro indicators similar to what we would expect based on the post-WWII, non-ZLB benchmark and by displaying stable parameter estimates when compared to this benchmark. Finally, Van Zandweghe (2015) implements formal statistical tests that cannot reject the hypothesis that macroeconomic variables have the same relationship with a lagged shadow federal funds rate, since the start of the current recovery, as they had with the effective federal funds rate before the recession.

Second, by using a New Keynesian model for the United States, Wu and Zhang (2017) demonstrate that the impact of unconventional policies (specifically quantitative easing and lending facilities) on the economy is identical to that of negative shadow rates, making the latter a useful summary statistic for these policies. It can therefore be used as a convenient indicator for measuring the total accommodation provided by both conventional and unconventional policies.

However, there is uncertainty underlying any estimate of the shadow rate, as it is deduced from a statistical model and is not directly observed. Therefore, we use a set of three alternative shadow rates that are available for the euro area: the shadow rates by Kortela (2016), Lemke and Vladu (2016), and Wu and Xia (2017). Their models predominantly vary in terms of the specification of the lower bound imposed on short-term rates. Kortela (2016) incorporates a time-varying lower bound for nominal interest rates in the shadow rate model, in order to account for the recent changes of the deposit facility rate into negative territory. Lemke and Vladu (2016) use a shadow-rate model that allows for several shifts in the lower bound: for the period up to August 2015, they retain two deterministic sub-periods; for the period after August 2015, they calibrate the time-varying lower bound as the month-average of all daily minima of Overnight Indexed Swap (OIS) spot and forward curves. Wu and Xia (2017) propose a term structure model that allows for a time-varying lower bound through the introduction of (i) a regime-switching model for the deposit rate dynamics and (ii) a time-varying spread between the policy lower bound and the yield curve. The resulting shadow rates are displayed on Figure 1, along with the main monetary policy measures implemented in the euro area (black vertical lines). Although all shadow rates broadly share similar trends and exhibit high correlations (ranging from 0.96 to 0.97 in the full sample and ranging from 0.90 to 0.94 since 2008Q1), there may be differences in level which stem from the different choices in model specification. It is also clear from this plot that the main movements in shadow rates are strongly aligned with unconventional monetary policy announcements. For instance, the TLTRO announcement in 2014 is followed by the sharpest drop in shadow rates on average.

In order to account for measurement uncertainty, we extract one common factor from the set of the three alternative shadow rates. Our objective is to identify the factor that explains the commonalities between the three alternative measures, such that if the factor is held constant, the partial correlations among the alternative measures are all equal to zero. Therefore, the latent common factor is a driver of the three observed measures. In our analysis, we directly introduce all three alternative measures in the structural model to endogenously extract their common factor, which we ultimately use as the representative shadow rate.

3. Estimating a Macroeconomic Model Using Shadow Rates

This section presents the structural model used for quantifying the macroeconomic effects of unconventional policies, and discusses the estimation results on the 1999Q1-2017Q2 period.

3.1. **The structural model.** The model combines a neoclassical growth core with several shocks and frictions (see Smets and Wouters, 2007; Justiniano et al., 2010). It includes features such as habit formation, investment adjustment costs, variable capital utilization, monopolistic competition in goods and labor markets, and nominal price and wage rigidities. The economy is populated by five classes of agents: producers of a final good, intermediate goods' producers, households, employment agencies and the public sector (government and monetary authorities).[3] The nominal interest rate is assumed to be the representative shadow rate, obtained as a common factor of the three alternative shadow rates. Obviously, no transactions are taking place at the shadow rate, but various borrowing/lending rates that private agents face co-move with it, with correlations of about 0.9 (see Figure A1 of Appendix A). This strong link between bank rates and the shadow rate has also been documented by Wu and Zhang (2017) in the case of the United States. This indicates that the shadow rate has comparable dynamics to the borrowing/lending rates (notably to the 3-month government bond rate, the underlying counterpart in the model, which becomes negative from mid-2014) and that the difference in levels results from the additional easing of financing conditions provided by the non-standard measures.

3.1.1. *Household sector.*

Employment agencies–. Each household indexed by $j \in [0,1]$ is a monopolistic supplier of specialized labor $N_{j,t}$. At every point in time t, a large number of competitive "employment agencies" combine households' labor into a homogenous labor input N_t sold to intermediate firms, according to $N_t = \left[\int_0^1 N_{j,t}^{\frac{1}{\varepsilon_{w,t}}} \mathrm{d}j\right]^{\varepsilon_{w,t}}$. Profit maximization by the perfectly competitive employment agencies implies the labor demand function $N_{j,t} = \left(\frac{W_{j,t}}{W_t}\right)^{-\frac{\varepsilon_{w,t}}{\varepsilon_{w,t}-1}} N_t$, where $W_{j,t}$ is the wage paid by employment

[3]In the following, we let variables without a time subscript denote steady-state values.

agencies to the household supplying labor variety j, while $W_t \equiv \left(\int_0^1 W_{j,t}^{\frac{1}{\varepsilon_{w,t}-1}} \mathrm{d}j\right)^{\varepsilon_{w,t}-1}$ is the wage paid by intermediate firms for the homogenous labor input sold to them by the agencies. The exogenous variable $\varepsilon_{w,t}$ measures the substitutability across labor varieties and its steady-state is the desired steady-state wage mark-up over the marginal rate of substitution between consumption and leisure.

Household's preferences–. The preferences of the jth household are given by

$$\mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \varepsilon_{b,t+s} \left(\log \left(C_{t+s} - hC_{t+s-1} \right) - \frac{N_{j,t+s}^{1+\nu}}{1+\nu} + \mathcal{V} \left(G_{t+s} \right) \right),$$

where E_t denotes the mathematical expectation operator conditional upon information available at t, $\beta \in (0,1)$ is the subjective discount factor, $h \in [0,1]$ denotes the degree of habit formation, and $\nu > 0$ is the inverse of the Frisch labor supply elasticity. C_t denotes consumption, $N_{j,t}$ is labor of type j, and $\varepsilon_{b,t}$ is a preference shock. Finally, $\mathcal{V}(.)$ is a positive concave function.

Household j's period budget constraint is given by

$$P_t \left(C_t + I_t \right) + T_t + B_t \leq S_{t-1} B_{t-1} + A_{j,t} + D_t + W_{j,t} N_{j,t} + \left(R_t^k u_t - P_t \vartheta \left(u_t \right) \right) \bar{K}_{t-1},$$

where I_t is investment, T_t denotes nominal lump-sum taxes (transfers if negative), B_t is the one-period riskless bond, S_t is the nominal interest rate on bonds, $A_{j,t}$ is the net cash flow from household's j portfolio of state contingent securities, D_t is the equity payout received from the ownership of firms. The capital utilization rate u_t transforms physical capital $\bar{K}_t$ into the service flow of effective capital K_t according to $K_t = u_t \bar{K}_{t-1}$, and the effective capital is rented to intermediate firms at the nominal rental rate R_t^k. The costs of capital utilization per unit of capital is given by the convex function $\vartheta \left(u_t \right)$. We assume that $u = 1$, $\vartheta \left(1 \right) = 0$, and we define $\eta_u \equiv \left[\vartheta'' \left(1 \right) / \vartheta' \left(1 \right) \right] / \left[1 + \vartheta'' \left(1 \right) / \vartheta' \left(1 \right) \right]$.[4] The physical capital accumulates according to

$$\bar{K}_t = \left(1 - \delta \right) \bar{K}_{t-1} + \varepsilon_{i,t} \left(1 - \Psi \left(\frac{I_t}{I_{t-1}} \right) \right) I_t,$$

where $\delta \in [0,1]$ is the depreciation rate of capital, and $\Psi \left(. \right)$ is an adjustment cost function which satisfies $\Psi \left(\gamma_z \right) = \Psi' \left(\gamma_z \right) = 0$ and $\Psi'' \left(\gamma_z \right) = \eta_k > 0$, γ_z is the steady-state (gross) growth rate of technology, and $\varepsilon_{i,t}$ is an investment shock. Households set nominal wages according to a staggering mechanism. In each period, a fraction θ_w of households cannot choose its wage optimally, but adjusts it to keep up with the increase in the general wage level in the previous period according to the indexation rule $W_{j,t} = \gamma_z \pi^{1-\gamma_w} \pi_{t-1}^{\gamma_w} W_{j,t-1}$, where $\pi_t \equiv P_t / P_{t-1}$ represents the gross inflation rate, π is steady-state (or trend) inflation and the coefficient $\gamma_w \in [0,1]$ is the degree of indexation to past wages. The remaining fraction of households chooses instead an optimal wage, subject to the labor demand function $N_{j,t}$.

[4] Later, we estimate η_u rather than the elasticity $\vartheta'' \left(1 \right) / \vartheta' \left(1 \right)$ to avoid convergence issues.

3.1.2. *Business sector.*

Final good producers–. At every point in time t, a perfectly competitive sector produces a final good Y_t by combining a continuum of intermediate goods $Y_t(\varsigma)$, $\varsigma \in [0,1]$, according to the technology $Y_t = \left[\int_0^1 Y_{\varsigma,t}{}^{\frac{1}{\varepsilon_{p,t}}} \mathrm{d}\varsigma\right]^{\varepsilon_{p,t}}$. Final good producing firms take their output price, P_t, and their input prices, $P_{\varsigma,t}$, as given and beyond their control. Profit maximization implies $Y_{\varsigma,t} = \left(\frac{P_{\varsigma,t}}{P_t}\right)^{-\frac{\varepsilon_{p,t}}{\varepsilon_{p,t}-1}} Y_t$ from which we deduce the relationship between the price of the final good and the prices of intermediate goods $P_t \equiv \left[\int_0^1 P_{\varsigma,t}{}^{\frac{1}{\varepsilon_{p,t}-1}} \mathrm{d}\varsigma\right]^{\varepsilon_{p,t}-1}$. The exogenous variable $\varepsilon_{p,t}$ measures the substitutability across differentiated intermediate goods and its steady state is then the desired steady-state price markup over the marginal cost of intermediate firms.

Intermediate-goods firms–. Intermediate good ς is produced by a monopolistic firm using the following production function

$$Y_{\varsigma,t} = K_{\varsigma,t}{}^{\alpha} \left[Z_t N_{\varsigma,t}\right]^{1-\alpha} - Z_t \Omega,$$

where $\alpha \in (0,1)$ denotes the capital share, $K_{\varsigma,t}$ and $N_{\varsigma,t}$ denote the amounts of capital and effective labor used by firm ς, Ω is a fixed cost of production that ensures that profits are zero in steady state, and Z_t is an exogenous labor-augmenting productivity factor whose growth-rate is denoted by $\varepsilon_{z,t} \equiv Z_t / Z_{t-1}$. In addition, we assume that intermediate firms rent capital and labor in perfectly competitive factor markets.

Intermediate firms set prices according to a staggering mechanism. In each period, a fraction θ_p of firms cannot choose its price optimally, but adjusts it to keep up with the increase in the general price level in the previous period according to the indexation rule $P_{\varsigma,t} = \pi^{1-\gamma_p} \pi_{t-1}^{\gamma_p} P_{\varsigma,t-1}$,where the coefficient $\gamma_p \in [0,1]$ indicates the degree of indexation to past prices. The remaining fraction of firms chooses its price $P^{\star}_{\varsigma,t}$ optimally, by maximizing the present discounted value of future profits

$$\mathrm{E}_t \sum_{s=0}^{\infty} \left(\beta\theta_p\right)^s \frac{\Lambda_{t+s}}{\Lambda_t} \left\{\Pi^p_{t,t+s} P^{\star}_{\varsigma,t} Y_{\varsigma,t+s} - \left[W_{t+s} N_{\varsigma,t+s} + R^k_{t+s} K_{\varsigma,t+s}\right]\right\},$$

where

$$\Pi^p_{t,t+s} = \begin{cases} \prod_{v=1}^{s} \pi^{1-\gamma_p} \pi_{t+v-1}^{\gamma_p} & s > 0 \\ 1 & s = 0, \end{cases}$$

subject to the demand from final goods firms and the production function. Λ_{t+s} is the marginal utility of consumption for the representative household that owns the firm.

3.1.3. *Public sector.* Fiscal policy is fully Ricardian. The government finances its budget deficit by issuing short-term bonds. Public spending is determined exogenously as a time-varying fraction of output

$$G_t = \left(1 - \frac{1}{\varepsilon_{g,t}}\right) Y_t,$$

where $\varepsilon_{g,t}$ is a government spending shock.

The monetary authority follows a shadow-rate Taylor rule by gradually adjusting the nominal interest rate in response to inflation, and output growth:

$$\frac{S_t}{S} = \left(\frac{S_{t-1}}{S}\right)^{\varphi_s} \left[\left(\frac{\pi_t}{\pi}\right)^{\varphi_\pi} \left(\frac{Y_t}{\gamma_z Y_{t-1}}\right)^{\varphi_y}\right]^{(1-\varphi_s)} \varepsilon_{s,t},$$

where $\varepsilon_{s,t}$ is a monetary policy shock. The parameter φ_s captures the degree of interest-rate smoothing.

In order to reduce a set of three shadow rate measures $S_{1,t}, S_{2,t}, S_{3,t}$ to a single variable S_t that contains information that is shared by the first set, we use a common factor structure and embed it directly in the model:

$$\begin{cases} \dfrac{S_{1,t}}{S_1} = \dfrac{S_t}{S}\varepsilon_{s1,t} \\ \dfrac{S_{2,t}}{S_2} = \dfrac{S_t}{S}\varepsilon_{s2,t} \\ \dfrac{S_{3,t}}{S_3} = \dfrac{S_t}{S}\varepsilon_{s3,t} \end{cases}$$

where $\varepsilon_{s1,t}, \varepsilon_{s2,t}, \varepsilon_{s3,t}$ are shocks capturing the idiosyncratic variance of each measure.

3.1.4. *Market clearing and stochastic processes.* Market clearing conditions on the final goods market are given by

$$Y_t = C_t + I_t + G_t + \vartheta(u_t)\bar{K}_{t-1},$$

$$\Delta_{p,t} Y_t = \left(u_t \bar{K}_{t-1}\right)^{\alpha} \left(Z_t N_t\right)^{1-\alpha} - Z_t \Omega,$$

where $\Delta_{p,t} = \int_0^1 \left(\frac{P_{\varsigma,t}}{P_t}\right)^{-\frac{\varepsilon_{p,t}}{\varepsilon_{p,t}-1}} d\varsigma$ is a measure of the price dispersion.

Regarding the properties of the stochastic variables, productivity and monetary policy shocks evolve according to $\log(\varepsilon_{x,t}) = \zeta_{x,t}$, with $x \in \{z, s\}$. The remaining exogenous variables follow an AR(1) process $\log(\varepsilon_{x,t}) = \rho_x \log(\varepsilon_{x,t-1}) + \zeta_{x,t}$, with $x \in \{b, i, g, p, w\}$. In all cases, $\zeta_{x,t} \sim i.i.d. \mathcal{N}\left(0, \sigma_x^2\right)$.

3.2. **Bayesian inference.**

3.2.1. *Macroeconomic data and econometric approach.* The quarterly euro area data run from 1999Q1 to 2017Q2 and are extracted from the ECB Statistical Database Warehouse, except for working age population. Inflation π_t is measured by the first difference of the logarithm of the core HICP deflator (excluding food and energy) which is a more relevant measure for policy purposes (Cai et al., 2018), and real wage growth $\Delta \log(W_t/P_t)$ is the first difference of the logarithm of the nominal wage divided by the GDP deflator. Output growth $\Delta \log Y_t$ is obtained as the first difference of the logarithm of real GDP, consumption growth $\Delta \log C_t$ is the first difference of the logarithm of real consumption expenditures, investment growth $\Delta \log I_t$ is the first difference of the logarithm of real gross investment. The monthly shadow rates $S_{1,t}, S_{2,t}$, and $S_{3,t}$ are the estimates of Kortela (2016), Lemke and

Vladu (2016) and Wu and Xia (2016), respectively. They are transformed into quarterly averages. Real variables are divided by the working age population, extracted from the OECD Economic Outlook. Total hours worked N_t are taken in logarithms. We use growth rates for the non-stationary variables in our data set (GDP, consumption, investment and the real wage) and express gross inflation, gross interest rates and the first difference of the logarithm of hours worked in percentage deviations from their sample means.

After normalizing trending variables by the stochastic trend component in labor factor productivity, we log-linearize the resulting systems in the neighborhood of the deterministic steady state (see Appendix B). Let $\boldsymbol{\theta}$ denote the vector of structural parameters and $\mathbf{v}_t$ be the r-dimensional vector of model variables. Thus, the state-space form of the different model specifications is characterized by the state equation $\mathbf{v}_t = \mathbb{A}(\boldsymbol{\theta})\mathbf{v}_{t-1} + \mathbb{B}(\boldsymbol{\theta})\boldsymbol{\zeta_t}$, where $\boldsymbol{\zeta_t} \sim i.i.d.N\left(0, \Sigma_\zeta\right)$ is the q-dimensional vector of innovations to the structural shocks, and $\mathbb{A}(\boldsymbol{\theta})$ and $\mathbb{B}(\boldsymbol{\theta})$ are complicated functions of the model's parameters $\boldsymbol{\theta}$. The measurement equation is given by $\mathbf{x}_t = \mathbb{C}(\boldsymbol{\theta}) + \mathbb{D}\mathbf{v}_t + \mathbb{E}\mathbf{e}_t$, where $\mathbf{x}_t$ is an n-dimensional vector of observed variables, $\mathbb{D}$ and $\mathbb{E}$ are selection matrices, $\mathbf{e}_t$ is a vector of measurement errors, and $\mathbb{C}(\boldsymbol{\theta})$ is a vector that is a function of the structural parameters.

We follow the Bayesian approach to estimate the model (see An and Schorfheide, 2007, for an overview). The posterior distribution associated with the vector of observables is computed numerically using a Monte Carlo Markov Chain (MCMC) sampling approach.

Specifically, we rely on the Metropolis-Hastings algorithm to obtain a random draw of size 1,000,000 from the posterior distribution of the parameters. The likelihood is based on the following vector of observable variables:

$$\mathbf{x}_t = 100 \times [\Delta \log Y_t, \Delta \log C_t, \Delta \log I_t, \Delta \log \left(W_t/P_t\right), \Delta \log N_t, \pi_t, S_{1,t}, S_{2,t}, S_{3,t}].$$

where Δ denotes the temporal difference operator.

3.2.2. *Estimation results.* The benchmark model contains eighteen structural parameters, excluding the parameters relative to the exogenous shocks. We calibrate six of them: The discount factor β is set to 0.998, the capital depreciation rate δ is equal to 0.025, the parameter α in the Cobb-Douglas production function is set to 0.30 to match the average capital share in net (of fixed costs) output (McAdam and Willman, 2013), the steady-state price and wage markups ε_p and ε_w are set to 1.20 and 1.35 respectively (Everaert and Schule, 2008), and the steady-state share of government spending in output is set to 0.20 (the average value over the sample period). The remaining twelve parameters are estimated. The prior distribution is summarized in the second column of Table 1. Our choices are in line with the literature, particularly with Smets and Wouters (2007), Sahuc and Smets (2008) and Justiniano, Primiceri and Tambalotti (2010).

Table 1. Prior densities and posterior estimates

Parameter	Prior	Posterior			
		1999Q1-2017Q2		1999Q1-2007Q4	
		Mean	90% CI	Mean	90% CI
Habit in consumption, h	$\mathcal{B}$ [0.70,0.10]	0.76	[0.68,0.83]	0.70	[0.58,0.80]
Elasticity of labor, ν	$\mathcal{G}$ [2.00,0.75]	2.21	[1.01,3.35]	2.07	[0.86,3.21]
Capital utilization cost, η_u	$\mathcal{B}$[0.50,0.10]	0.63	[0.50,0.75]	0.70	[0.58,0.82]
Investment adj. cost, η_k	$\mathcal{G}$[4.00,1.00]	5.28	[3.39,7.11]	4.18	[2.56,5.75]
Growth rate of technology, $\log(\gamma_z)$	$\mathcal{G}$[0.30,0.05]	0.26	[0.19,0.33]	0.27	[0.20,0.34]
Calvo price, θ_p	$\mathcal{B}$ [0.66,0.10]	0.89	[0.84,0.93]	0.82	[0.75,0.89]
Calvo wage, θ_w	$\mathcal{B}$ [0.66,0.10]	0.76	[0.64,0.88]	0.66	[0.50,0.82]
Price indexation, γ_p	$\mathcal{B}$[0.50,0.15]	0.32	[0.13,0.50]	0.40	[0.16,0.64]
Wage indexation, γ_w	$\mathcal{B}$[0.50,0.15]	0.40	[0.18,0.63]	0.40	[0.17,0.62]
Monetary policy-smoothing, φ_s	$\mathcal{B}$[0.75,0.15]	0.81	[0.77,0.86]	0.77	[0.70,0.85]
Monetary policy-inflation, φ_π	$\mathcal{G}$[1.70,0.30]	1.97	[1.55,2.39]	1.54	[1.20,1.86]
Monetary policy-output growth, φ_y	$\mathcal{G}$[0.125,0.05]	0.23	[0.11,0.36]	0.22	[0.09,0.34]
Wage markup shock persistence, ρ_w	$\mathcal{B}$[0.50,0.20]	0.84	[0.72,0.96]	0.94	[0.89,0.98]
Intertemporal shock persistence, ρ_b	$\mathcal{B}$[0.50,0.20]	0.39	[0.18,0.60]	0.31	[0.07,0.53]
Investment shock persistence, ρ_i	$\mathcal{B}$[0.50,0.20]	0.80	[0.69,0.91]	0.61	[0.43,0.80]
Price markup shock persistence, ρ_p	$\mathcal{B}$[0.50,0.20]	0.88	[0.79,0.98]	0.82	[0.65,0.97]
Government shock persistence, ρ_g	$\mathcal{B}$[0.50,0.20]	0.98	[0.97,0.99]	0.88	[0.76,0.99]
Wage markup shock (MA part), ϱ_w	$\mathcal{B}$[0.50,0.20]	0.58	[0.36,0.79]	0.66	[0.44,0.88]
Price markup shock (MA part), ϱ_p	$\mathcal{B}$[0.50,0.20]	0.67	[0.52,0.83]	0.54	[0.30,0.78]
Wage markup shock volatility, σ_w	$\mathcal{IG}$[0.25,2.00]	0.09	[0.07,0.11]	0.12	[0.08,0.15]
Intertemporal shock volatility, σ_b	$\mathcal{IG}$[0.25,2.00]	1.07	[0.70,1.42]	0.91	[0.50,1.29]
Investment shock volatility, σ_i	$\mathcal{IG}$[0.25,2.00]	0.24	[0.17,0.31]	0.19	[0.13,0.25]
Price markup shock volatility, σ_p	$\mathcal{IG}$[0.25,2.00]	0.05	[0.04,0.06]	0.06	[0.05,0.08]
Productivity shock volatility, σ_z	$\mathcal{IG}$[0.25,2.00]	0.65	[0.56,0.74]	0.56	[0.45,0.67]
Government shock volatility, σ_g	$\mathcal{IG}$[0.25,2.00]	0.32	[0.27,0.36]	0.27	[0.21,0.31]
Monetary policy shock volatility, σ_s	$\mathcal{IG}$[0.25,2.00]	0.14	[0.11,0.16]	0.11	[0.08,0.13]
Principal component shock 1 volatility, σ_{s1}	$\mathcal{IG}$[0.25,2.00]	0.08	[0.06,0.10]	0.06	[0.05,0.07]
Principal component shock 2 volatility, σ_{s2}	$\mathcal{IG}$[0.25,2.00]	0.15	[0.12,0.18]	0.06	[0.04,0.07]
Principal component shock 3 volatility, σ_{s3}	$\mathcal{IG}$[0.25,2.00]	0.20	[0.16,0.23]	0.05	[0.04,0.06]

Note: This table reports the prior distribution, the mean and the 90 percent confidence interval of the estimated posterior distribution of the structural parameters.

The estimation results are summarized in the right-hand side columns of Table 1, where the posterior mean and the 90% confidence interval are reported for the full sample 1999Q1-2017Q1 and for a pre-crisis sample 1999Q1-2007Q4. Based on the posterior mean, several results are worth commenting on.[5]

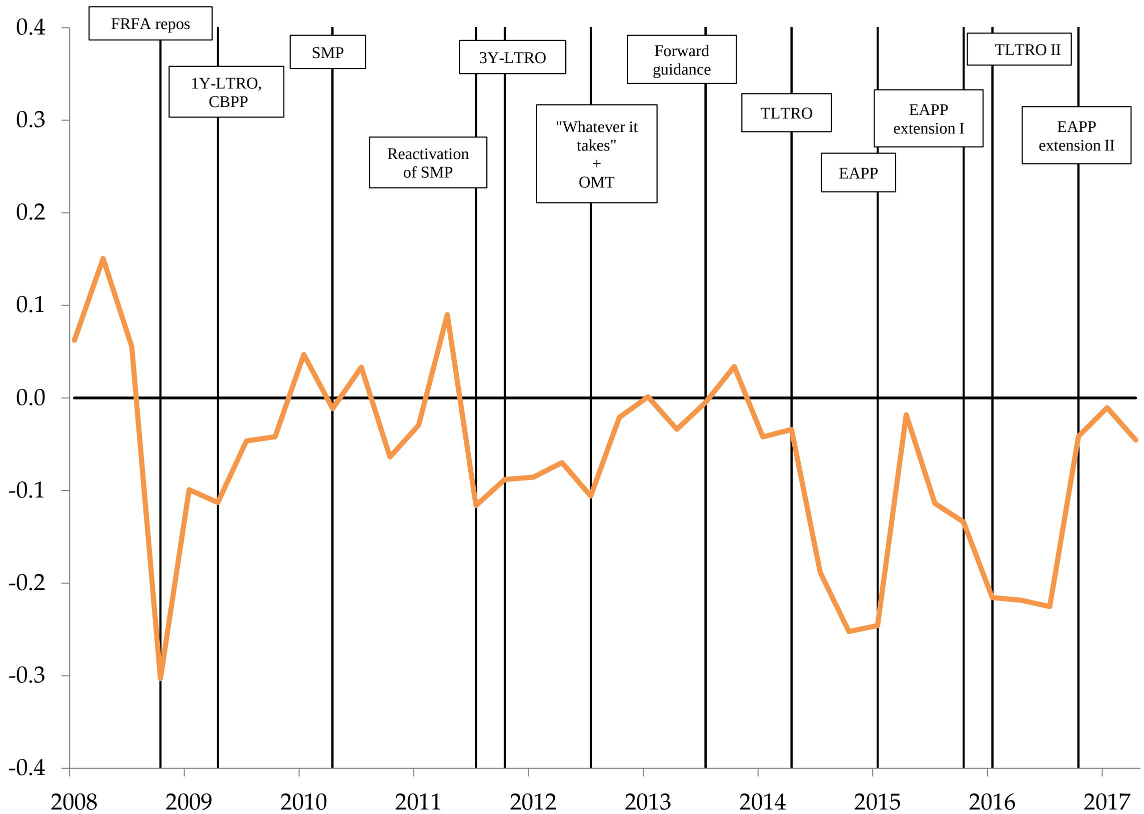
First, the estimated model parameters associated with the full sample are very close to those associated with the pre-crisis sample, suggesting that one can apply a DSGE model in a low-interest rate environment without observing any significant structural change. Indeed, the posterior means from one sub-sample are within the confidence intervals of the other sub-sample. We observe however an increase in nominal rigidities over the full sample. An impulse response analysis corroborates the fact that the responses to a monetary policy shock of the macroeconomic variables estimated in the full sample are consistent with those based on the shorter sample ending in 2007Q4 (see Figure B1 of Appendix B). This is in line with Debortoli, Gali and Gambetti (2018) who find that the dynamic responses of a number of U.S. macro variables to different shocks did not experience any major change during the ZLB period.

Second, all estimated values are consistent with most contributions in the medium-scale DSGE literature. With regard to the behavior of households, our estimate of the inverse of the elasticity of labor dis-utility, ν, is equal to 2.21 and the habit parameter h rises to 0.76, indicating that the reference for current consumption is more than 75% of past consumption. The probability that firms are not allowed to re-optimize their price is $\theta_p \approx 0.89$, implying an average duration of price contracts of about two years. With respect to wages, the probability of no change is $\theta_w \approx 0.76$, implying an average duration of wage contracts of about 12 months. All these numbers are consistent with the results reported in the survey by Druant, Fabiani, Kezdi, Lamo, Martins and Sabbatini (2012). In addition, the wage indexation parameter is $\gamma_w \approx 0.40$, which is higher than the price indexation parameter $\gamma_p \approx 0.32$. This reflects a now standard result that euro-area data do not require too high a degree of price or wage indexation to match the persistence in the data. Monetary policy parameters $(\phi_\pi, \phi_y) \approx (1.97, 0.23)$ and $\phi_s \approx 0.81$ indicate that the systematic part of monetary policy displays gradualism and a larger weight on inflation when focusing on the full sample than on the pre-crisis sample. Finally, as expected, we find that the volatility of the measurement errors associated with the three shadow rates become different only when the crisis period is taken into account.

Figure 2 plots the estimated monetary policy shocks along with dates of unconventional monetary policy announcements. We observe a crude alignment between the two: (i) during the period 2008-2017, monetary policy shocks are essentially negative, as expected; (ii) these negative shocks coincide with major policy announcements, such as FRFA tender, OMT, TLTRO, EAPP and TLTRO II.

[5]Section 2 of the Online Appendix offers additional model diagnostics (prior and posterior density plots, multivariate convergence diagnostics, unconditional variance decomposition) suggesting that there are no identification or stability issues.

Figure 2. Estimated monetary policy shocks



Note: The black vertical lines represent, respectively, the announcements of the main monetary policy measures implemented in the euro area: October 2008 (FRFA repos), June 2009 (1Y-LTRO and CBPP), May 2010 (SMP), August 2011 (Reactivation of SMP), December 2011 (3Y-LTRO), July 2012 ("Whatever it takes"), September 2012 (OMT), June 2013 (Forward guidance), June 2014 (TLTRO), January 2015 (EAPP), December 2015 (EAPP extension I), March 2016 (TLTRO II) and December 2016 (EAPP extension II).

4. Quantifying the macroeconomic effects of the ECB's unconventional measures

This section presents our quantitative assessment of the actual stimulus to real activity and price and wage inflation provided by the ECB's policies since 2008, based on counterfactual simulation analysis.

4.1. **Simulation design.** In order to assess the state of the economy in the absence of the ECB's policies, we must build counterfactual scenarios. To this end, we proceed as follows:

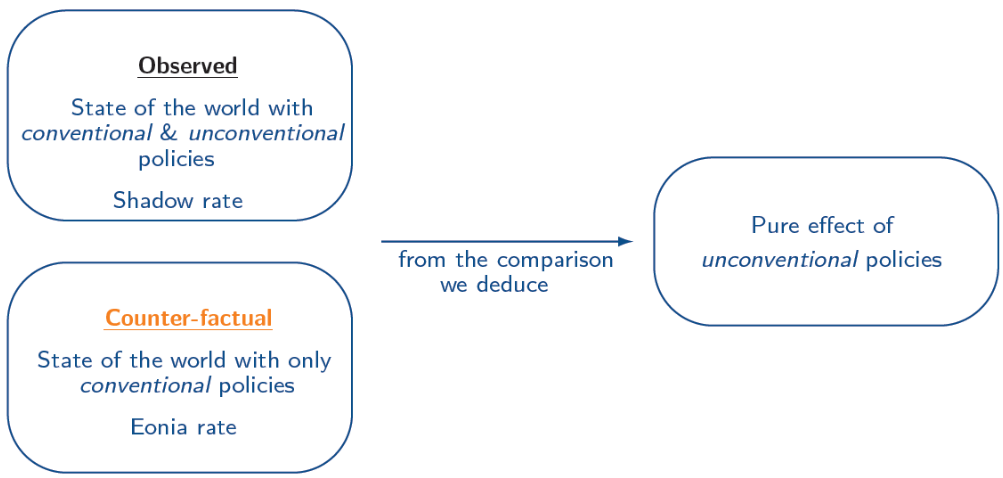
(1) We take the mean of the posterior estimates of the structural parameters and compute the associated estimates of monetary policy shocks using the Kalman filter. These shocks are those stemming from all monetary policy decisions, both conventional and unconventional ones ("observed").

(2) We then replace the observed monetary policy shocks with shocks that would have kept the shadow rate at the Eonia rate level, holding all other parameters fixed at their value obtained in step 1 ("counterfactual"). Technically, at each date, we must find the (monetary policy) shock that aligns the shadow rate to the Eonia rate and recompute the level of all variables according to the endogenous dynamics of the model and this new value of the shock.

(3) We then compute the simulated time-paths for the observed variables from the full estimated model with shadow rate using the first and second sets of monetary policy shocks.

Figure 3 illustrates the counterfactual exercise that allows us to deduce the pure effects of unconventional policies.

Figure 3. The counterfactual exercise

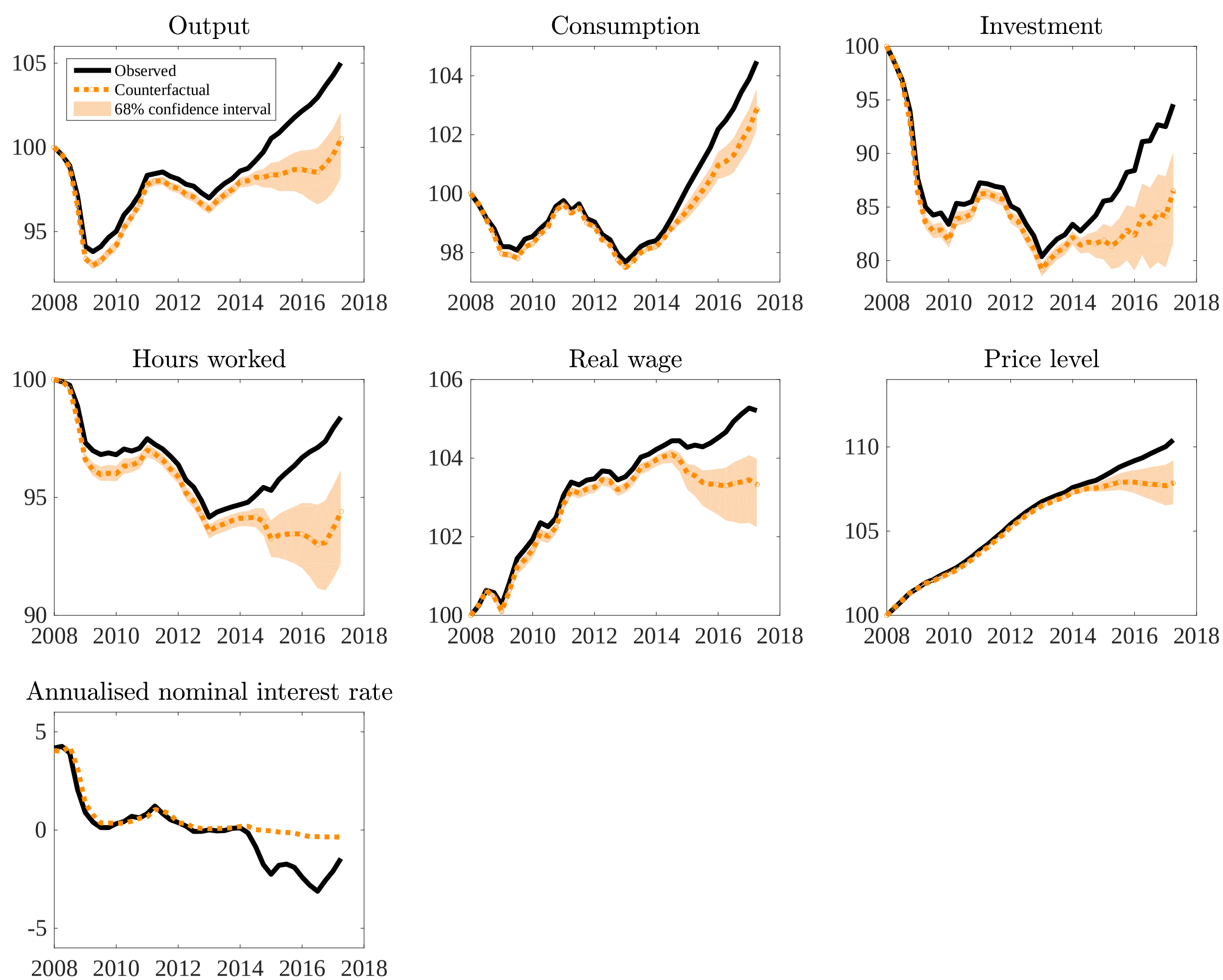


4.2. **Baseline evaluation.** Figure 4 plots the levels of the observed quarterly variables and their counterfactual estimates. In order to facilitate reading, all paths have been normalized to 100 in 2008Q1, with the exception of the interest rate which starts at its historical value. We clearly show that, without unconventional monetary policy measures, all macroeconomic variables would have been lower.

Major differences between the two series are visible in the early years of the financial crisis and from 2014 onwards. Indeed, in response to the 2008-2009 crisis, faced with distressed financial intermediaries, the ECB embarked in longer-term refinancing operations (LTROs) with full allotment, with maturities of three, six, and finally twelve months in July 2009.[6] Through these operations, the average maturity of outstanding liquidity was increased, from approximately 20 days before the crisis to more than 200 days in the second half of 2009. Cahn, Matheron and Sahuc (2017) find that such liquidity injections have played a key role in adverting a major credit crunch in the euro area.

[6]The amounts borrowed at these facilities were substantial, roughly 5% of annual euro area GDP for 3-month LTROs, slightly less than 2% for 6-month LTROs, and about 6.5% for 12-month LTROs.

Figure 4. Observed quarterly series and counterfactual estimate for the euro area



Note: Confidence intervals are built using 10 000 draws from the posterior distribution of the structural parameters.

Since 2014, the macroeconomic climate in the euro area has been characterized by increased risks threatening price stability and the anchoring of inflation expectations. In this context, the ECB adopted a threefold response (see, Marx et al., 2016). First, there was a succession of cuts in the deposit facility rate, from 0% in early 2014 to -0.40% in March 2016. These rate-cuts complemented the forward guidance policy already put in place since July 2013.[7] Second, in order to increase support for lending, a targeted longer-term refinancing operations (TLTRO) program, with attractive associated interest rates over a period of two years, has been implemented in July 2014. The objective of TLTROs is to: (i) encourage banks to lend more to non-financial corporations and to households and (ii) send a signal about future short-term rates, since loans were allotted fully and at a fixed rates (with early repayment possible without penalty). Third, public and private sector asset purchase programs have been conducted. In October 2014, the Eurosystem launched a first package of quantitative easing in the form of a dual purchase program of private sector assets aimed at promoting high-quality securitization and reducing the risk premium inflating the lending rates to Non-Financial Corporations (NFCs). In January 2015, the ECB decided to expand the previous asset purchase program to include public sector securities. The monthly purchases of public and private sector securities under this expanded asset purchase program were carried out between March 2015 and March 2016 for a total amount of EUR 60 billion per month. In December 2015, the asset purchase program was extended until at least March 2017. In March 2016 the ECB announced a new extension of the program, comprising of an increase in the monthly amount of purchases under the asset purchase program from EUR 60 billion to EUR 80 billion, the inclusion of investment grade bonds issued by NFCs in the scope of the asset purchase program, and the launch of a series of four targeted longer-term refinancing operations (TLTRO II). In December 2016 the ECB announced a recalibration of the asset purchase program, extending the net purchases until December 2017 but at a reduced monthly pace of EUR 60 billion from April 2017. The net purchases are to be made alongside reinvestments of the principal payments from maturing securities purchased under the asset purchase program.[8]

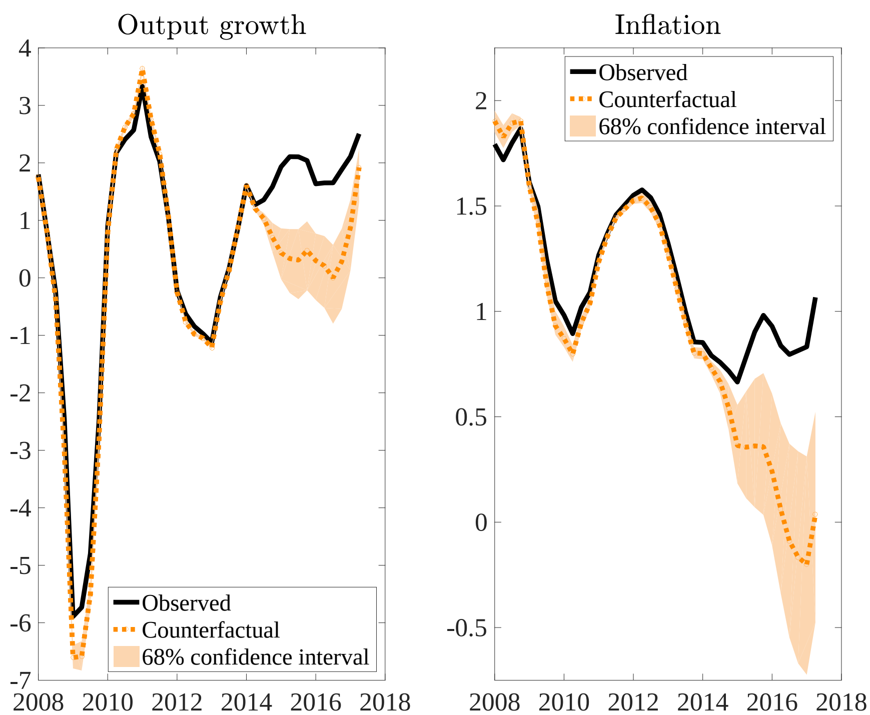
Our results show that quarterly output would have been 4.5% lower in 2017Q2 were it not for unconventional policies. The preponderance of this effect stems from the large decline in quarterly investment, which would have been about 8% below its actual level. The difference in the price level is more modest (around 2.6% in 2017Q2). The muted effect of QE on inflation, relative to GDP, is corroborated by Andrade, Breckenfelder, De Fiore, Karadi and Tristani (2016) and Sahuc (2016). More importantly, we note that unconventional measures have helped avoid a period of deflation from

[7]This forward guidance corresponds to a commitment on the future path of interest rates, so as to influence not only the short-term rates but also longer-term rates which are largely determined by expectations of future short-term rates.

[8]The ECB also adjusted the parameters of the APP as of January 2017 as follows. First, the maturity range of the public sector purchase program will be broadened by decreasing the minimum remaining maturity for eligible securities from two years to one year. Second, purchases of securities under the APP with a yield to maturity below the interest rate on the ECB's deposit facility will be permitted to the extent necessary.

mid-2015 to early 2017. This translates into year-on-year (y-o-y) inflation and GDP growth differentials of 0.26% and 0.51% on average over the period 2008Q1-2017Q2, respectively. Drawing attention on the period 2014Q1-2016Q1, when public and private sector asset purchase programs have been announced and conducted, y-o-y inflation and GDP growth would have been lower by 0.61% and 1.09%, respectively (Figure 5).

Figure 5. Year-on-year euro area output growth and inflation rates *(percent)*



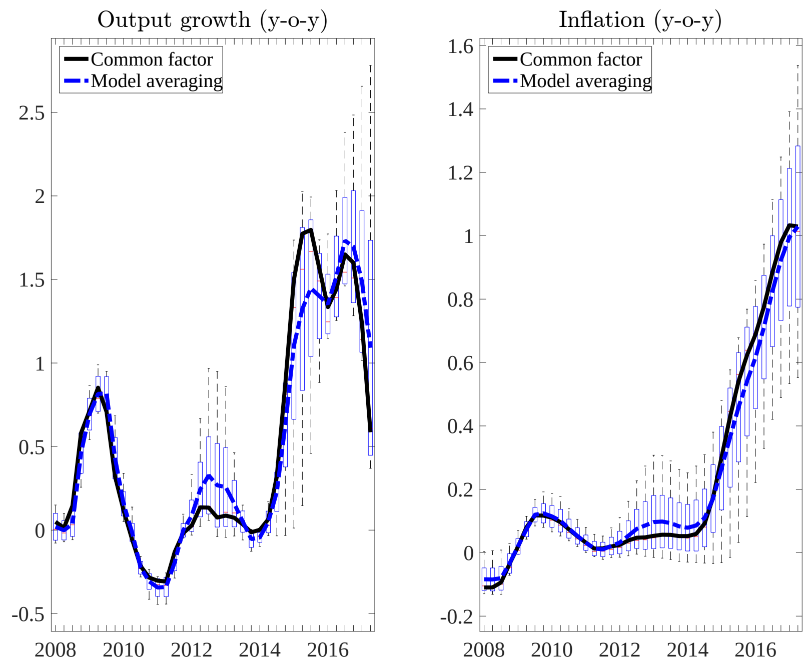
Note: Confidence intervals are built using 10 000 draws from the posterior distribution of the structural parameters.

Gauging the impact of unconventional monetary policies depends on which shocks are driving fluctuations. The historical contribution of the different types of shocks to GDP growth and inflation show that, although the dominant source of secular shifts in inflation is driven by price and wage markup shocks, monetary policy plays a significant positive role over the 2008-2017 period (see Figure C1 of Appendix C).

Using an estimated two-region DSGE model, that combines data on government debt stocks and yields across maturities, Hohberger, Priftis and Vogel (2017) find similar effects. Specifically, between 2015Q1 and 2016Q2, their shock decompositions suggest a positive average contribution of the ECB asset purchases to output growth and inflation of up to 0.7% and 0.4%, respectively, depending on the presence of a temporarily binding zero-bound constraint. These figures are relatively consistent with ours, and the difference with our quantification can be attributed to the gain brought by the other implemented measures, such as TLTROs or forward guidance.

Moreover, Damjanovic and Masten (2016) estimate a small VAR model, for the euro area, with output, prices and a shadow rate. They report that an unconventional monetary policy shock that decreases the shadow rate by 100 basis points increases euro-area output by about 0.7% and increases prices by about 0.2%. In line with our findings, the effect on inflation is more muted than on real activity.

Figure 6. Euro-area unconventional policy gains from alternative shadow rates *(percent)*



Note: The black line represents the percentage gain when using the shadow rate extracted from the common factor analysis. The dotted line represents the percentage gain computed in averaging the results obtained with the four shadow rates. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The outliers are plotted individually using the '+' symbol.

4.3. **Robustness.** This section reports two robustness exercises. In the first one, we compute the distribution of the gains made by unconventional policies across the different shadow rates. In the second one, we assess the effects of the magnitude of the intertemporal elasticity of substitution.

4.3.1. *Individual estimation across different shadow rates.* We reproduce the same exercise as in the previous section for each shadow-rate measure individually. This allows us to have a distribution of the gains made by unconventional policies across the four indicators (the three available measures and the latent common factor). A standardized way of displaying such a distribution is to use a non-parametric box plot that graphically depicts the gains through their quartiles. Figure 6 shows box plots for y-o-y output growth and y-o-y inflation rates and provides two interesting results. First, the distribution can be quite large when shadow rates fall into negative territory, with deviations up to 1% for output growth and 0.5% for inflation. Second, to account for the uncertainty surrounding the shadow rate, an econometrician could prefer using an average of the results obtained with each of the available indicators ("model averaging"). In this case, we see that the gains are similar to those obtained using the "common factor" indicator.

4.3.2. *Estimation of the degree of relative risk aversion.* Given that the magnitude of the intertemporal elasticity of substitution changes the responsiveness of consumption relative to the interest rate, we re-estimate our model by replacing the logarithmic specification of the utility of consumption by a CES specification:

$$\mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \varepsilon_{b,t+s} \left(\frac{\left(C_{t+s} - hC_{t+s-1}\right)^{1-\sigma} - 1}{1-\sigma} - Z_t^{1-\sigma} \frac{N_{j,t+s}^{1+\nu}}{1+\nu} + \mathcal{V}\left(G_{t+s}\right) \right).$$

The key findings are the following. First, the estimate of the inverse of the intertemporal elasticity of substitution σ is equal to 1.43, a value close to the one obtained by Smets and Wouters (2007) (see Table D1 in Appendix D). Importantly, the calibrated value of 1 (logarithmic specification) happens to fall within the confidence interval of the estimation of the CES specification. Second, counterfactuals are very similar: the y-o-y inflation and GDP growth would have been on average about 0.74% and 0.96% below their actual levels over the period 2014Q1-2017Q2, respectively (see Figure D1 in Appendix D).

4.4. **A comparison with the United States.** It is interesting to compare the figures obtained for the euro area with those emanating from the effects of the US unconventional measures. In fact, the United States used unconventional monetary policy measures from the beginning of the financial crisis and entered in a "normalization phase" at the end of 2015.[9] This provides us a well-defined period during which the effects of policies can be measured.

While the federal funds target was at the zero lower bound, the Fed attempted to provide additional stimulus through unsterilized purchases of Treasury and mortgage-backed securities, a practice referred to as quantitative easing. Between 2009 and 2014, the Fed undertook three rounds of quantitative easing. The third round was completed in October 2014, at which point the Fed's balance sheet was USD 4.5 trillion, five times its pre-crisis size. In December 2015, having decided that economic

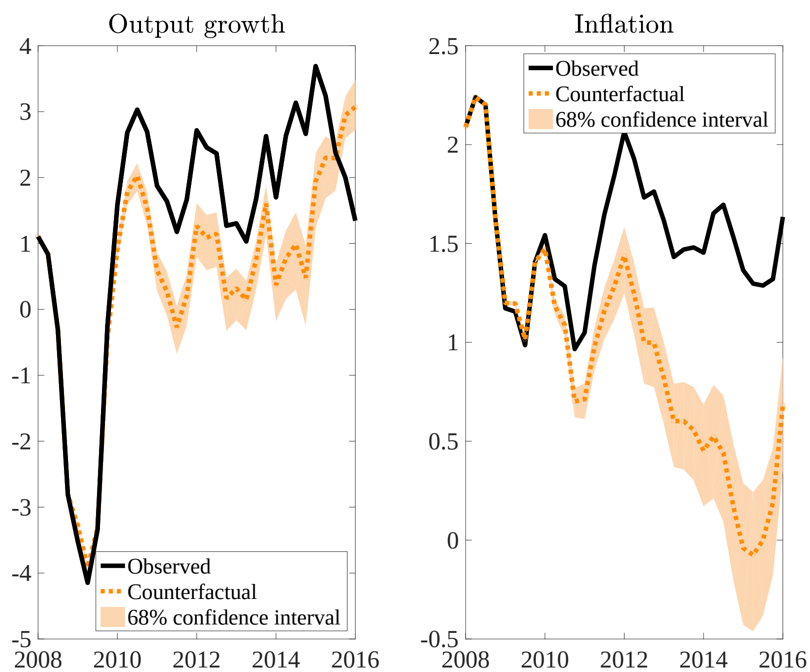
[9]The Federal Open Market Committee introduced its approach to monetary policy normalization in the "Policy Normalization Principles and Plans", outlining a three-step normalization strategy: First, the Fed would gradually raise policy rates to "normal levels", second, it would begin to reduce its balance sheet in a "gradual and predictable manner", and third, it would gradually transform its asset holdings to a composition similar to that of the pre-crisis period thanks to a reduction in the average maturity of its assets and a decrease in its large holdings of agency debt and agency MBS.

conditions and the economic outlook warranted a rate hike, it raised its target federal funds rate for the first time in seven years to a range of between 0.25% and 0.5%. The Fed has raised interest rates in the presence of a large balance sheet through the use of two new tools, by raising the rate of interest paid to banks on reserves and by engaging in reverse repurchase agreements (reverse repos) through a new overnight facility.

We therefore reproduce an exercise identical to that carried out for the euro area but in estimating the DSGE model on US data (over the period 1999Q1-2017Q2).[10] We obtain year-on-year (y-o-y) inflation and GDP growth differentials of 0.6% and 0.92% on average over the period 2008Q1-2015Q4, respectively (Figure 7).

Two points of comparison are interesting to put forward. Unlike in the euro area, the effects are more homogeneous, probably due to the three rounds of quantitative easing over the period. Second, while the euro area has not yet entered a normalization stage, the average macroeconomic effects (up to 2017Q2) are of the same order than the transatlantic ones (until 2015Q4).

Figure 7. Year-on-year US output growth and inflation rates *(percent)*



Note: Confidence intervals are built using 10 000 draws from the posterior distribution of the structural parameters.

[10]US data are taken from the FRED database: GDP growth (GDPC96), consumption growth (PCEC), investment growth (FPI), wage growth (PRS85006103), weekly hours (PRS85006023), GDP deflator (GDPDEF), core PCE (JCXFE), civilian employment (CE16OV), civilian non-institutional population (LNU00000000Q), Federal funds rate (FEDFUNDS). The US shadow rate is the one by Wu and Xia (2016). A comparison of the fed funds rate and the shadow rate is provided in Figure OA3 of the Online Appendix.

5. Concluding remarks

In this paper, we estimate a medium-scale DSGE model in which the policy rate is replaced by a shadow rate, and perform counterfactual analyses. This allows us to quantify the macroeconomic effects of the European Central Bank's unconventional monetary policies. Overall, our results suggest that, without unconventional measures, the euro area would have suffered *(i)* a substantial loss of output since the Great Recession and *(ii)* a period of deflation from mid-2015 to early 2017. This translates into year-on-year inflation and GDP growth differentials of 0.61% and 1.09%, respectively, over the period 2014Q1-2017Q2.

Our analysis also highlights that we can still use standard DSGE models in low interest rate environments when using an unconstrained proxy of the monetary policy stance such as the shadow rate. Indeed, the introduction of the shadow rate allows us to bypass problems associated with the ELB, especially when the latter varies over time as in the euro area. It makes the approach appealing from a policy point of view because evaluations can be easily made using traditional tools.

However, there are many extensions to this current work, both from a modeling and an econometric perspective. In particular, endogenously deriving the shadow rate within the structural model, by attempting to directly introduce a term structure into the model (along the lines of Ang and Piazzesi, 2003; Hordahl et al., 2006) would be a promising step. The complexity is that the shadow rate block remains nonlinear and therefore solving and estimating the model as a whole is not trivial.

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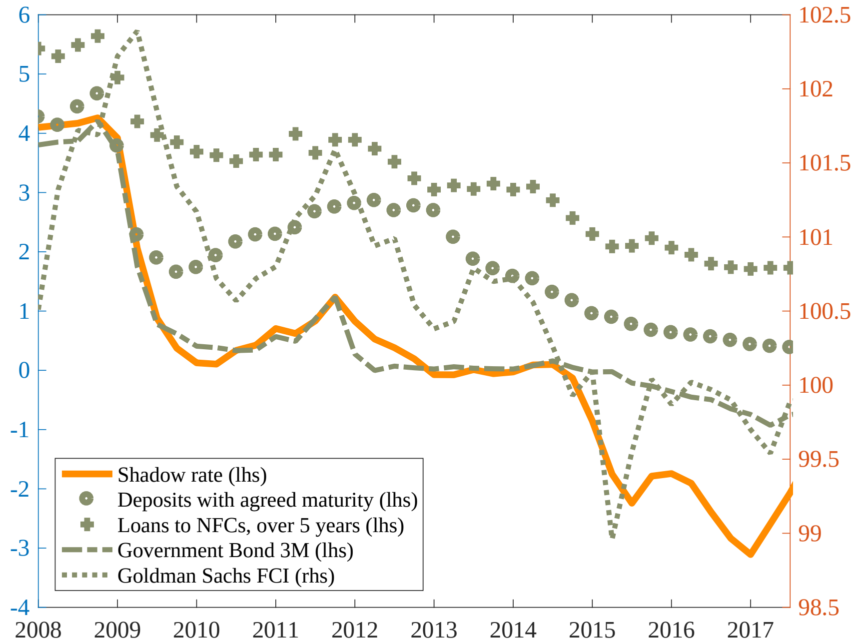
Appendix A: Shadow rate and key financial indicators

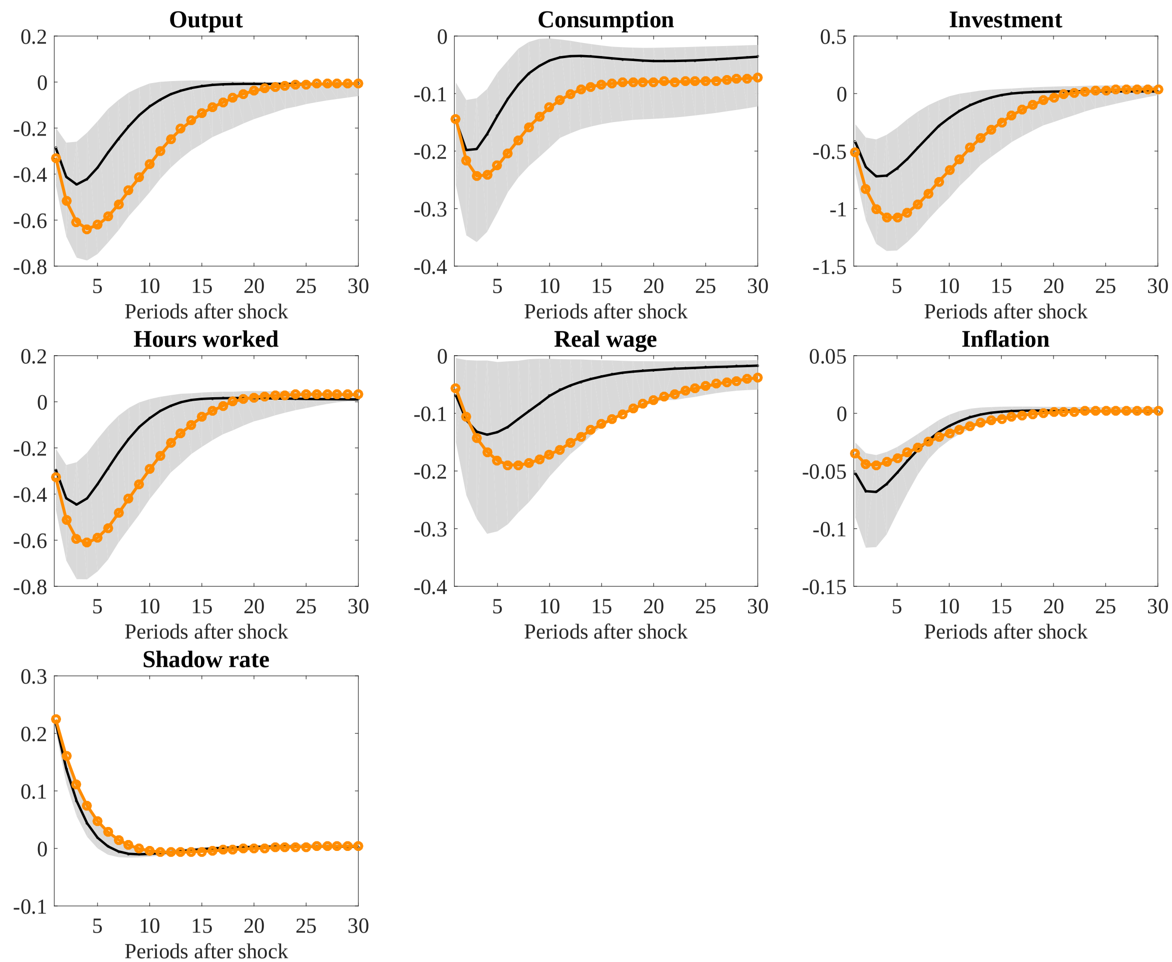
Figure A1. Private and public interest rates, financial condition index, and the shadow rate



Note: The orange line is the representative shadow rate (obtained as a common component of three alternative shadow rates) and the green lines represent: (i) the rate on deposits with agreed maturity for households (mainly time deposits with a given maturity that may be subject to the payment of a penalty in the event of early withdrawal); (ii) the rate on loans to Non-Financial Corporations (NFC) with maturity over 5 years; (iii) the nominal 3-month government bond yield, all issuers whose rating is between AAA and AA; (iv) the euro-area Goldman Sachs Financial Condition Index (FCI). Deposits and loans are new business. The source of private and public rates is the ECB-Statistical Data Warehouse and the source of the Goldman-Sachs FCI is Bloomberg.

Appendix B: Impulse Response Analysis

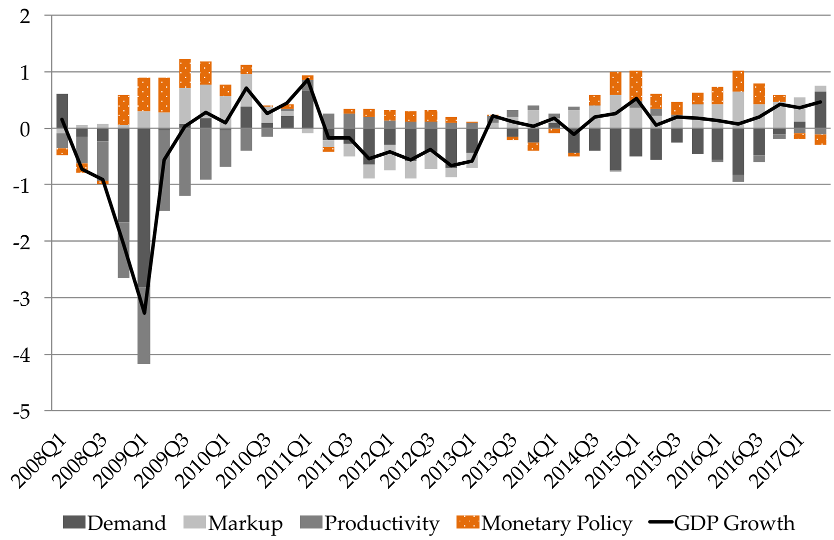
Figure B1. The impulse responses to a monetary policy shock

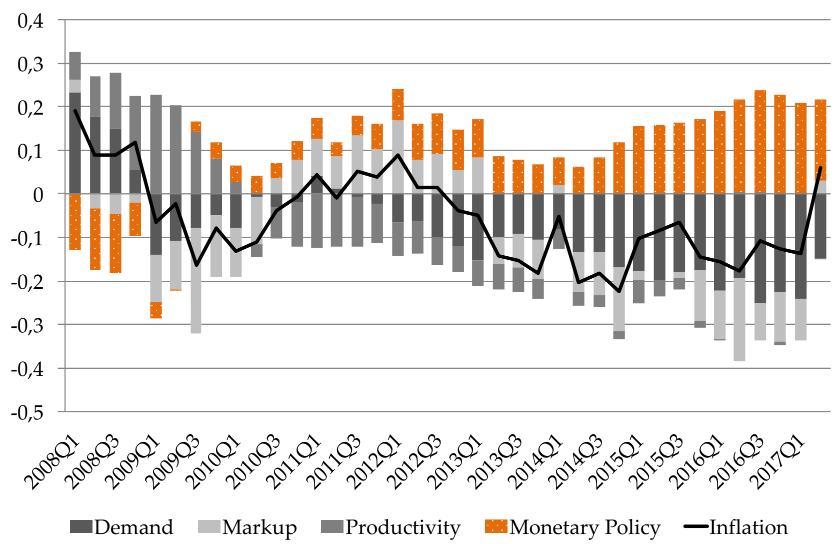


Note: The black line is the mean impulse response associated with the model estimated over the period 1999Q1-2007Q4 and the gray area is its 90 percent confidence region. The orange line is the mean impulse response associated with the model estimated over the period 1999Q1-2017Q2.

Appendix C: Historical decomposition of GDP growth and inflation

Figure C1. Historical decomposition of GDP growth (*top*) and inflation (*bottom*)





Note: The demand shocks include the preference, investment and government spending shocks; the markup shocks include the price and wage markup shocks. Quarterly mean inflation is estimated at 0.35 percent.

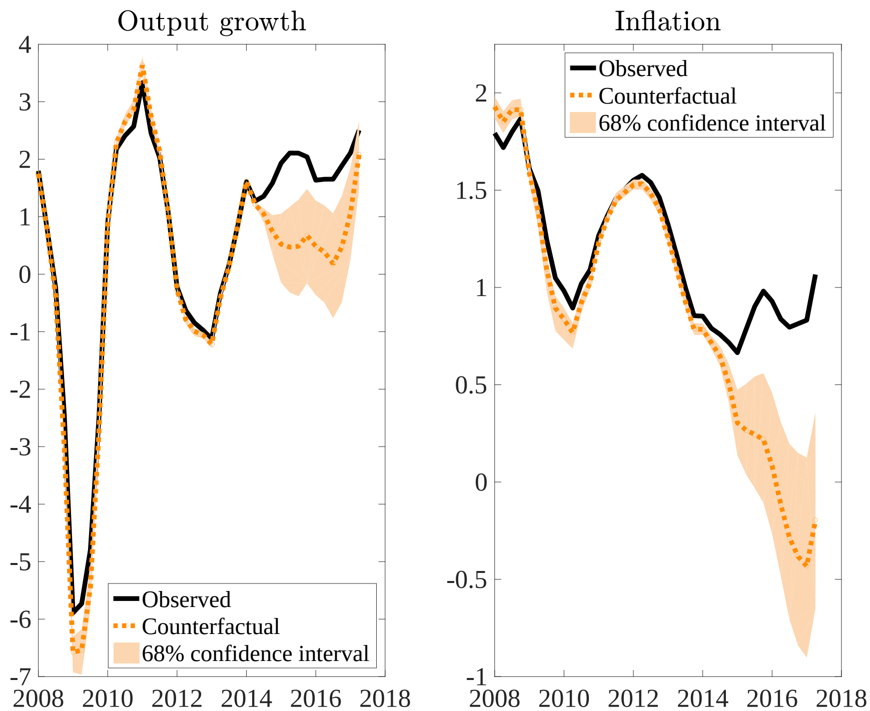
Appendix D: Results with an estimated intertemporal elasticity of substitution

Table D1. Prior densities and posterior estimates

Parameter	Prior	Posterior	
		Mean	90% Conf. Interval
Habit in consumption, h	$\mathcal{B}$ [0.70,0.10]	0.74	[0.64,0.83]
Elasticity of labor, ν	$\mathcal{G}$ [2.00,0.75]	2.37	[1.16,3.53]
Relative risk aversion, σ	$\mathcal{G}$ [1.00,0.50]	1.43	[0.89,1.93]
Capital utilisation cost, η_u	$\mathcal{B}$[0.50,0.10]	0.63	[0.51,0.76]
Investment adj. cost, η_k	$\mathcal{G}$[4.00,1.00]	5.12	[3.27,6.89]
Growth rate of technology, $\log(\gamma_z)$	$\mathcal{G}$[0.30,0.05]	0.27	[0.20,0.34]
Calvo price, θ_p	$\mathcal{B}$ [0.66,0.10]	0.89	[0.84,0.93]
Calvo wage, θ_w	$\mathcal{B}$ [0.66,0.10]	0.74	[0.63,0.86]
Price indexation, γ_p	$\mathcal{B}$[0.50,0.15]	0.32	[0.13,0.51]
Wage indexation, γ_w	$\mathcal{B}$[0.50,0.15]	0.42	[0.18,0.64]
Monetary policy-smoothing, ϕ_s	$\mathcal{B}$[0.75,0.15]	0.83	[0.78,0.87]
Monetary policy-inflation, ϕ_π	$\mathcal{G}$[1.70,0.30]	2.07	[1.61,2.50]
Monetary policy-output growth, ϕ_y	$\mathcal{G}$[0.125,0.05]	0.25	[0.11,0.39]
Wage markup shock persistence, ρ_w	$\mathcal{B}$[0.50,0.20]	0.85	[0.74,0.96]
Intertemporal shock persistence, ρ_b	$\mathcal{B}$[0.50,0.20]	0.45	[0.21,0.69]
Investment shock persistence, ρ_i	$\mathcal{B}$[0.50,0.20]	0.81	[0.70,0.92]
Price markup shock persistence, ρ_p	$\mathcal{B}$[0.50,0.20]	0.89	[0.80,0.99]
Government shock persistence, ρ_g	$\mathcal{B}$[0.50,0.20]	0.98	[0.97,0.99]
Wage markup shock (MA part), ϱ_w	$\mathcal{B}$[0.50,0.20]	0.58	[0.37,0.79]
Price markup shock (MA part), ϱ_p	$\mathcal{B}$[0.50,0.20]	0.66	[0.50,0.82]
Wage markup shock volatility, σ_w	$\mathcal{IG}$[0.25,2.00]	0.09	[0.07,0.11]
Intertemporal shock volatility, σ_b	$\mathcal{IG}$[0.25,2.00]	1.42	[0.75,2.06]
Investment shock volatility, σ_i	$\mathcal{IG}$[0.25,2.00]	0.25	[0.19,0.32]
Price markup shock volatility, σ_p	$\mathcal{IG}$[0.25,2.00]	0.05	[0.04,0.06]
Productivity shock volatility, σ_z	$\mathcal{IG}$[0.25,2.00]	0.65	[0.56,0.74]
Government shock volatility, σ_g	$\mathcal{IG}$[0.25,2.00]	0.31	[0.27,0.35]
Monetary policy shock volatility, σ_s	$\mathcal{IG}$[0.25,2.00]	0.14	[0.11,0.16]
Principal component shock 1 volatility, σ_{s1}	$\mathcal{IG}$[0.25,2.00]	0.08	[0.05,0.10]
Principal component shock 2 volatility, σ_{s2}	$\mathcal{IG}$[0.25,2.00]	0.15	[0.12,0.18]
Principal component shock 3 volatility, σ_{s3}	$\mathcal{IG}$[0.25,2.00]	0.19	[0.16,0.22]

Note: This table reports the prior distribution, the mean and the 90 percent confidence interval of the estimated posterior distribution of the structural parameters.

Figure D1. Year-on-year euro area output growth and inflation rates *(percent)*



Note: Confidence intervals are built using 10 000 draws from the posterior distribution of the structural parameters.