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How effective quantitative tightening can be with a higher-for-longer pledge?

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Abstract

We study the effect of quantitative tightening both without forward guidance and with higher for longer guidance. This is done by simulating quantitative tightening strategies in a dynamic stochastic general equilibrium model estimated with the euro area data. Quantitative tightening is quantified by a bond supply shock that raises the long-term term premium. Initially, we assume that quantitative tightening comes without forward guidance, meaning that central bank does not communicate any information regarding the future path of the policy rate. Subsequently, we consider quantitative tightening with forward guidance which is communicated through a higher for longer pledge. In addition, this higher for longer pledge is assumed to be fully credible. We find that if credible, quantitative tightening implemented with forward guidance in the form a higher for longer pledge can tighten monetary policy, albeit a little.

Keywords: monetary policy, quantitative tightening, forward guidance

JEL code: E52

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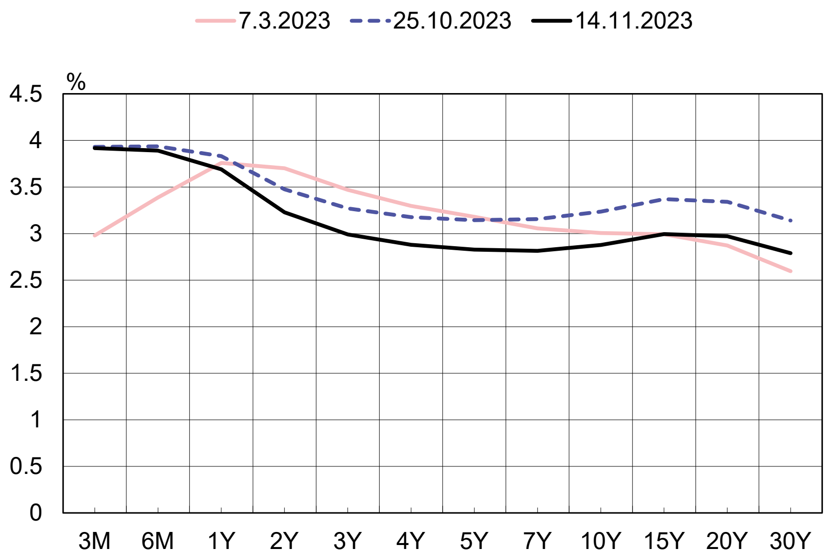
1 Introduction

In December 2021, the ECB decided to start rewinding its net asset purchases, both the Asset Purchase Programme (APP) and the Pandemic Emergency Purchase Programme (PEPP) during the first quarter of 2022. The acceleration of inflation in the aftermath of the pandemic and the Russian war in Ukraine speeded up the tightening of monetary policy. In July 2022, the ECB increased the key policy rate, the deposit facility rate (DFR), from -0.5% to zero percent. Until February 2024, the ECB has increased the DFR altogether by 4.5 percentage points.

In the ECB's October 2023 monetary policy statement, the ECB's president Lagarde stated the following:*" We are determined to ensure that inflation returns to our two per cent medium-term target in a timely manner. Based on our current assessment, we consider that rates are at levels that, maintained for a sufficiently long duration, will make a substantial contribution to the timely return of inflation to our target. Our future decisions will ensure that the key ECB interest rates will be set at sufficiently restrictive levels for as long as necessary to ensure such a timely return. We will continue to follow a data-dependent approach to determining the appropriate level and duration of restriction."*

Figure 1 Overnight index swap (OIS) curve for the euro area.



Source: Bloomberg. 32422@OIS_käyrä3

This communication is widely understood by the public so that the ECB policy rates are currently at restrictive levels and that the ECB is expecting the rates to stay at these levels for a prolonged period. Furthermore, some (e.g. Richter (2023)) have interpreted this communication as a pledge to keep the policy rates higher for longer. However, because the overnight index swap curve is lower after the above ECB announcement, the OIS-curve seems to indicate that the financial market is either not believing or understanding this pledge, see Figure 1.

This leaves room for the possibility that perhaps the central bank's forward guidance is not fully credible when the central bank operates above the effective lower bound. An alternative, and also plausible, interpretation is that the market expects inflation to return to the target faster than what the central bank thinks.

Balance sheet reduction is still a rather new policy and there exist only a few studies on quantitative tightening. Nevertheless, there exists a few sketches for future quantitative tightening in the euro area such as IMF (2023), Schnabel (2023), Claeys (2023), and European Parliament (2023). On the other hand, balance sheet expansion or quantitative easing has been studied a lot. In principle, the quantitative easing could mimic the quantitative tightening with just opposite sign. In practice, there are bound to be differences between quantitative easing and tightening due to e.g. the zero lower bound constraint on the interest rate and the size of the central bank balance sheet.

Most of the existing studies on quantitative easing have found meaningful positive effects on aggregate demand and inflation, see e.g. Bhattarai and Neely (2016), CGFS (2019), Martin and Milas (2012). However, Chen et al. (2012) finds smaller positive effects on aggregate demand. Furthermore, Ikeda et al (2020) find no meaningful short-run effect but larger positive effects in the long-term. An interesting finding is also that the quantitative easing studies conducted by central banks typically find it more efficient than those conducted in academia, see Fabo et al. (2021).

In this study, we apply Chen et al. (2012) model but first extend the model with so called Kimball price aggregation, see e.g. Lindé and Trabandt (2018). Second, we estimate the model with the euro area data. Third we do some policy simulations and ask what happens if in the current situation the ECB starts an active quantitative tightening with the APP and terminates the reinvestments of PEPP earlier than intended. We try this first without higher for longer pledge and then with it.

When quantitative tightening is done without the higher for longer pledge, the central bank is not communicating its likely interest rate path in advance. This lack of forward guidance suits well the current announced meeting-by-meeting and data dependent approach by the ECB. In model simulations the future policy rate is defined by the feedback rule that reacts to future growth and inflation. This generates an endogenous reaction of the policy rate to the quantitative tightening.

The higher for longer pledge is forward guidance. The central bank is communicating its likely interest rate path in advance. Public (households and firms) can only see the current policy rate with certainty. How trustworthy this higher for longer pledge is in the eyes of public depends crucially on how credible the central bank is assumed to be. In simulations, we assume that when the central bank communicates higher for longer pledge that it is fully credible. This assumption of credibility allows us to treat the policy rate as given (exogenous) for some periods.

We find that a realistically sized quantitative tightening shock, which mimics the current ECB's balance sheet policy has only a small impact. Moreover, we find that quantitative tightening without a higher for longer pledge has only small effects. In the simulations this is because of the aforementioned endogenous policy rate reaction, where the interest rate reacts to the growth and inflation.

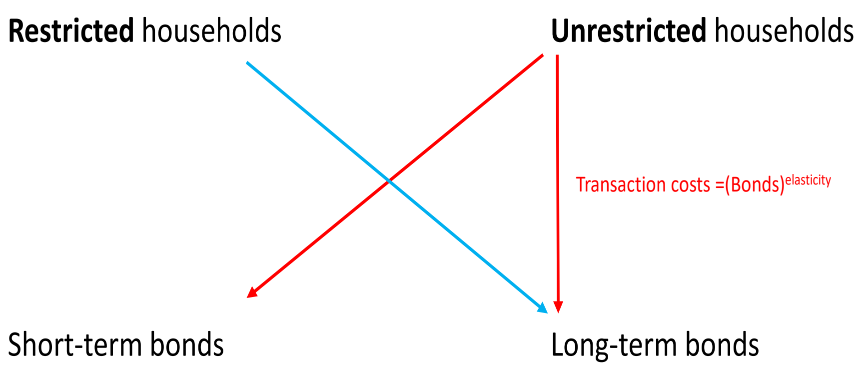
In addition, we find that quantitative tightening with a higher for longer pledge, if it is presumed credible, does have some favorable stance effects and could potentially be an important tool. This is because the endogenous policy rate reaction is now effectively blocked. However, these effects are still small for a realistic calibration of the quantitative tightening shock, even if we assume full credibility (of which the current data show only limited evidence).

In what follows, and before turning to simulations and the results, we lay down the sketch of a DSGE model, Chen et al. (2012), we utilize.

2 Model

To study the effect of a higher for longer pledge and quantitative tightening we utilize the Chen et al. (2012) model. The defining feature of the model is that the households are divided to two groups according to their savings patterns (aka Two Agent New Keynesian (TANK) economy), see Figure 2.

Figure 2 Households' savings



Households in the first group, the so-called restricted households, can only invest in long-term bonds if they want to smooth their consumption intertemporally. Households in the second group, the so-called unrestricted households, can however invest both in short-term and long-term bonds. The latter group, nevertheless, must pay transaction costs (a premium) if they invest in the long-term markets.

Endogenized term premium is due to the assumed premium that the unrestricted households must pay to invest in long term markets. This premium or a transaction cost is related to the quantity of debt with some (estimated) elasticity.

As the restricted households cannot buy short-term bonds, this construct could be described as a limited participation or market segmentation model. The obvious benefit of this construct is that it introduces a financial friction that breaks Wallace neutrality and hence allows possibly nontrivial effects of quantitative easing or tightening[1].

The rest of the Chen et al. (2012) model is a rather standard closed economy general equilibrium model. Perfectly competitive labor agencies combine differentiated labor inputs into a homogenous labor composite according to the constant elasticity of substitution technology. Profit maximization gives the demand for the differentiated labor input as a function of relative wages and aggregate labor demand. Households are monopolistic suppliers of differentiated labor input and set wages on a staggered basis as in Calvo (1983) taking the demand as given.

Capital goods producers maximize the expected discount stream of dividends to their shareholders subject to the capital accumulation dynamics and convex real adjustment costs. Capital producers also choose the utilization rate and rent the effective capital to intermediate goods producers.

Perfectly competitive final goods producers combine differentiated intermediate goods. The cost minimization of final goods producers yields demand for the differentiated intermediate good as a function of relative prices and aggregate output.

Monopolistic competitive intermediate goods producers rent capital from capital goods producers and combine it with the labor hired from labor agencies to produce intermediate goods according to a standard Cobb-Douglas technology. Intermediate goods producers set prices on a staggered basis as in Calvo (1983). We nevertheless deviate from the original Chen et al. (2012) model by using Kimball price aggregation à la Linde and Trabandt (2018), see Appendix 1. As Kimball aggregation is more general formulation than Dixit-Stiglitz aggregation we also test these variants against each other in Appendix 2.

[1] Wallace (1981) neutrality theorem says that any open-market operation is not affecting the economy and therefore asset purchases or sales are irrelevant. There are various ways to break this neutrality e.g. Vayanos and Vila (2009) use a preferred habitat model that also has market segmentation as the Chen et al. (2012) model. An alternative way is to allow the central bank to operate directly on the credit market and therefore on the supply on credit in the economy, see Gertler and Karadi (2011). One could also think that liquidity and collateral aspects of open-market operations as well as the central bank's losses (without transferring them back to the private investors through the treasury) might break Wallace's neutrality, see Benigno et al. (2020).

The feedback rule for the central bank is essentially same as in Taylor (1993), but with interest rate smoothing and using the growth rate in output, instead of the output gap. The supply of long-term government bonds follows autoregressive rule for the detrended market value of public debt in real terms. Fiscal rule assumes that the government adjusts the real primary fiscal surplus in response to the lagged real value of long-term debt. Furthermore, we write the fiscal policy rule in a stationary form.

In addition, when defining the innovation processes, we apply autoregressive processes for all shocks. Moreover, we drop the lump sum tax shock and apply only a government consumption shock as a fiscal shock.

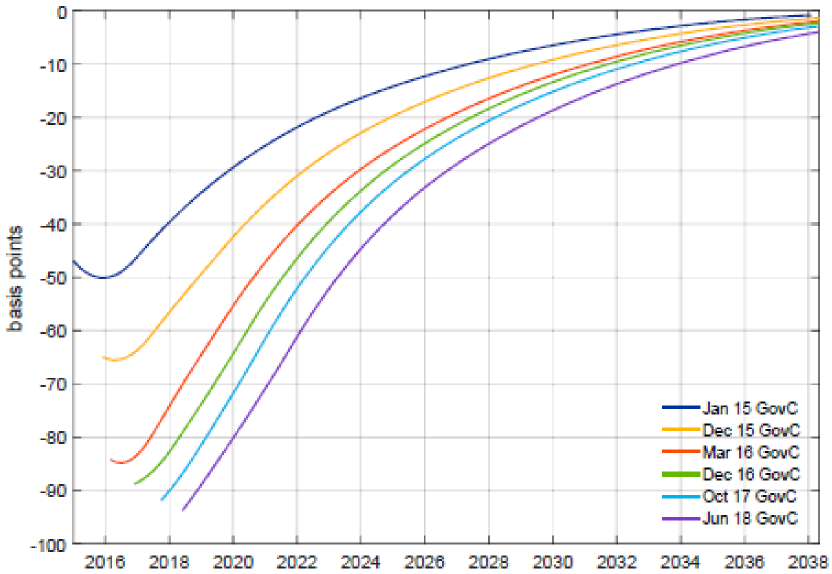
3 Estimation

We estimate the Chen et al. (2012) model with Kimball price aggregation for euro area data 1999Q1-2014Q1. The model is estimated by standard Bayesian methods and the estimation results, along with chosen prior distributions, are shown in Appendix 2. We report model's behavior by showing the reactions of model's key variables to productivity, fiscal and monetary policy shocks. All the impulse response functions of these shocks yield reasonable behavior. Furthermore, we show the historical and real time decompositions after the estimation period of some key variables with respect to the shocks and find these also reasonable. Finally, we also show that testing of the price aggregation favors Kimball price aggregation relative to Dixit-Stiglitz aggregation.

4 Simulations

We calibrate the quantitative tightening shock as follows. First, we look at the announcement effect of the APP program. In January 2015, the ECB announced a monthly purchase of 60 bn euros from March 2015 onwards for the following 19 months totaling to about 1.14 tn euros. Eser et al. (2019) estimated that this announcement decreased 10-year term premium by about 50 basis point on impact, see Figure 3.

Figure 3 10-year term premium (QE).



Source: Eser et al. (2019).

We assume that the quantitative tightening shock is symmetric (with respect to a quantitative easing shock) on its effect on the term premium. This does not need to be so but since we do not have any evidence otherwise, we treat it as symmetric. Regarding the size of the quantitative tightening shock, we assume the PEPP reinvestments are discontinued from the beginning of 2024. In addition, we assume an active quantitative tightening as suggested, for example by Rabobank, see Central Banking (2023). We assume that would total to about 300 bn euros and would correspond to about 1/3 of the announcement effect on term premium of the above APP shock in 2015, see Figure 4.[2,3]

Here, as also with other simulation exercises, we assume that the initial shock impulse is unanticipated. Thereafter the innovations are assumed to follow estimated autoregressive pattern.

Next, we simulate a quantitative tightening shock which generates an increase of the long-term time premium by 17bps on impact and follows thereafter the estimated persistence structure. This shock is shown (red lines) in Figure 5 below. Notice, that here and below in all simulations the impulse responses are shown as deviations from the model's steady state (baseline), and do not show for example the actual level of the interest rates.

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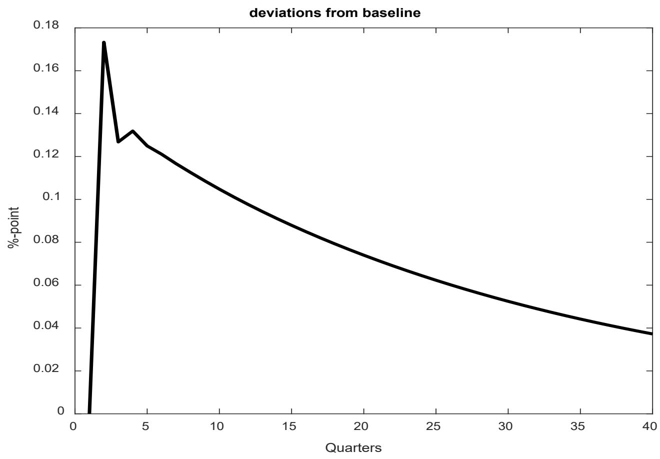
[2] ING (2022) bank assumed that quantitative tightening in 2024 would amount about 300 bn euros.
[3] In technical terms, we shock the supply of bonds by increasing the supply of long-term bonds as the central banks sells these back to the financial market. The price of these bonds falls as the supply increases and therefore the long-term interest rate (including the term premium) increases.

Figure 4 Calibrated effect of the quantitative tightening shock on 10-year term premium.



The shock is indeed persistent with the half-life of the shock in about 5 years. The effect on the long-term interest rate is only 7bps on impact. Long-term rates fall less than the long-term premium as it also depends on the expected path of the short-term interest rate, which falls. In addition, we assume here no forward guidance of the policy rate which reacts according to the estimated policy function. This reaction leads to almost immediate loosening of the policy rate by a couple of basis points, but the effect is very persistent. All in all, this steepens the term structure of interest rates while lowering the short-term interest rate.

The ex ante real rate increases only a little for two quarters but falls then below zero for the next ten years. This small fall in the real rate boosts investment and consumption somewhat, which improves output growth in the short run. Inflation rate nevertheless falls due to the increase in the long-term interest rate.

In Chen et al. (2012) the term premium affects consumption of households through the budget constraint. The unconstrained households that can invest to both short and long-term bonds have an opportunity to ride along the yield depending on the change in the term premium. The constrained households on the other hand do not have this opportunity and must react to the shifts in the term premium. Changes in the term premium also affects government spending through the changes in the government budget constraint. Investment changes are more indirect and are due to the general equilibrium effects. How big these effects are, depends crucially on the degree of financial market segmentation as well as on the estimated semi-elasticity of the risk-premium with respect to the private held public debt both of which are estimated to be small.

Next, we consider quantitative tightening shock with a two-year higher for longer pledge that is understood and believed by all agents in the economy. This shock is shown (in green lines) in Figure 6. Now the policy rate is held steady at the current level for two years as promised. This and the fall in the inflation rate yield an increase in the expected real rate. This increase in the *ex ante* real rate decreases investment and consumption slightly leading to an immediate fall in output growth paralleling the fall in the conventional policy hike.

Figure 5 Quantitative tightening shock without higher for longer pledge

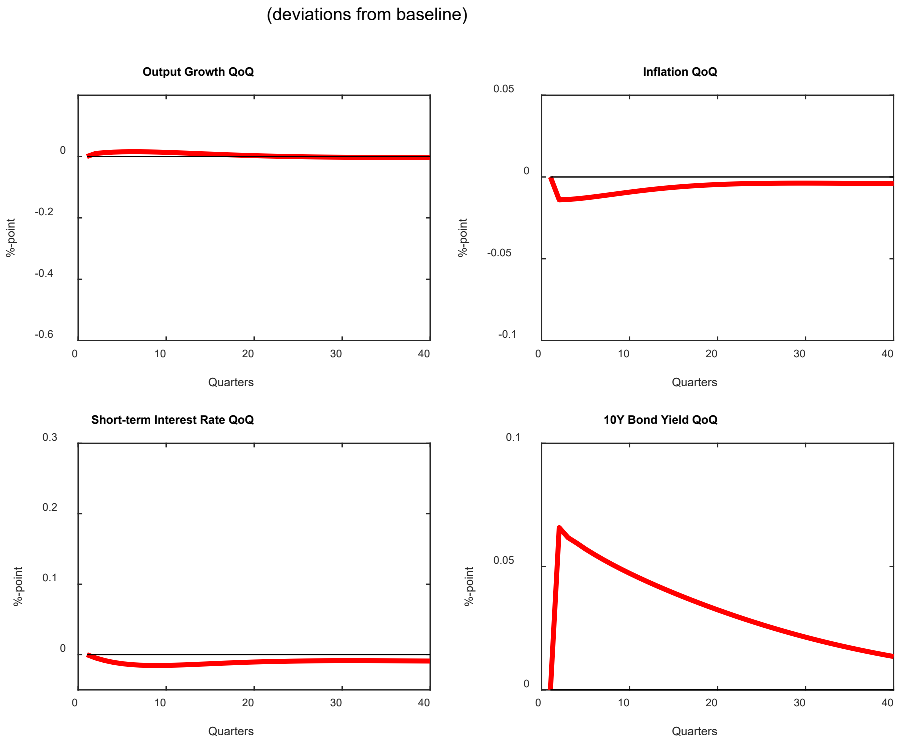


Figure 6 Quantitative tightening shock with credible higher for longer pledge for two years.

(deviations from baseline)

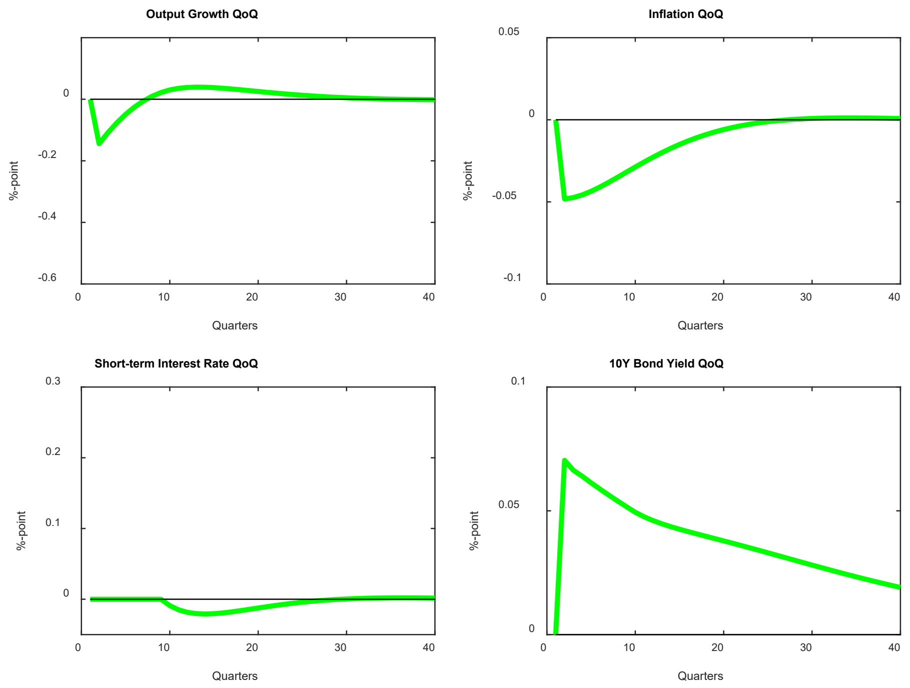
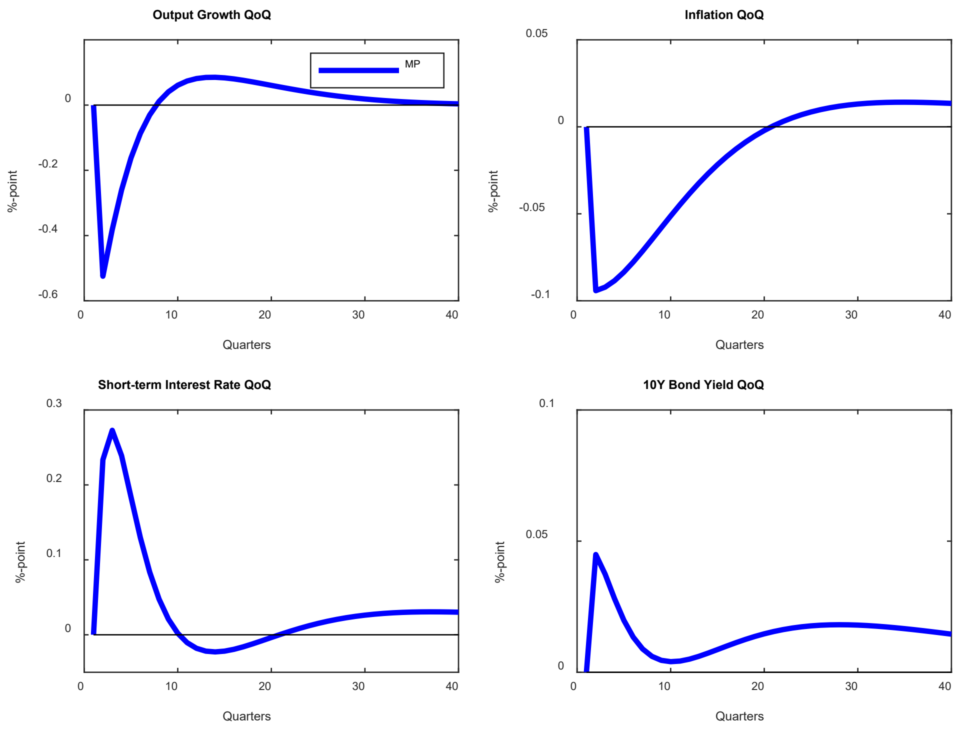


Figure 7 Temporary Monetary Policy Shock.

(deviations from baseline)



To understand the magnitude of the quantitative tightening shock we compare above quantitative tightening shocks with and without the higher for longer pledge to a standard persistent monetary policy shock where the policy rate is increased unexpectedly by 25bps for one period and then fades away after two years, see Figure 7 (blue lines).

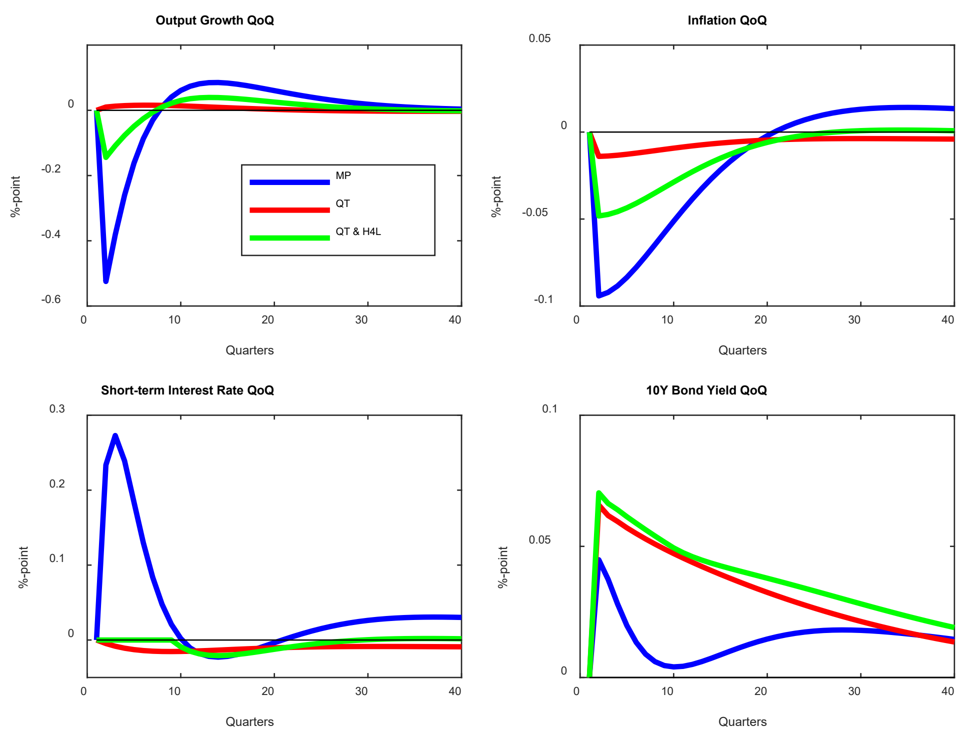
The shock leads to an immediate fall of the quarterly output growth rate by about half of percentage point. Annual inflation rate falls only of 0.1 percentage point. Long-term interest rate increases only a little.

Finally, we stack all the above simulations for comparison purposes in Figure 8. We see immediately that a conventional policy rate shock is more efficient with respect to output and inflation than either quantitative tightening strategies.

One way to frame these simulations is to note that quantitative tightening is effectively decreasing non-borrowed reserves in the economy and hence has a direct liquidity channel. Forward guidance concerning the future policy rates via the higher for longer pledge on the other hand operates through the signaling channel. In practice, however, doing active quantitative tightening might also constitute a signaling effect especially since it might be costly for the central bank to do so.

Figure 8 Policy rate shock vs. quantitative tightening vs. quantitative tightening with higher for longer pledge.

(deviations from baseline)



5 Discussion about the results

The model applied in the simulations is obviously very stylized to highlight the complex interplay of conventional monetary policy (policy rate decisions) and unconventional monetary policy (balance sheet policies). Nevertheless, it carries some advantages such as endogenous determination of the term premium. Furthermore, the version used in policy simulations is estimated with the euro area data.

The model is written as a closed economy model with rational expectations, and assuming there are no other financial market frictions which would require modelling of monetary policy transmission through financial intermediaries such as banks. We also assumed that there are no liquidity constrained households. Model could be extended in these and many other dimensions but acknowledging these limitations, the simplified model structure we apply focuses on the interplay of conventional and unconventional monetary policy.

The results first indicate that implemented with a higher for longer pledge or not, the effects of the quantitative tightening will be relatively small with a reasonable calibration of a quantitative tightening shock. Hence, quantitative tightening with reasonable calibration is not a game changer.

Second, looking at quantitative tightening without higher for longer pledge, we see that quantitative tightening has only tiny effects. Much of the effects of quantitative tightening are eaten away by the endogenous policy rate reaction.

Third, however, if credible forward guidance can be applied in the form of a higher for longer pledge with quantitative tightening, then we can observe stronger, albeit still small, effects. So, if a credible higher for longer pledge can be applied with quantitative tightening, then this can be used as a moderate monetary policy tool.

Furthermore, comparing a reasonably calibrated quantitative tightening with an ordinary monetary policy hike of 25bps, we can see that the latter would do the same trick.

The quantitative tightening shock should be calibrated to a much bigger size than we have done here to have stronger effects. However, this seems very unlikely especially as it effectively means that the central banks would realize larger losses. In addition, an increase in the term premium could increase the risk of higher fragmentation in the euro area sovereign bond markets and possibly a need to resort to the Transmission Protection Instrument, which could then quickly reverse the intended effects of quantitative tightening.

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Appendix 1 Kimball Aggregation

We assume Kimball aggregation as in Lindé and Trabandt (2018).

Final Goods Producers

The final good Y_t is a composite made of a continuum of goods indexed by $i \in (1,1)$:

$$1 = \left[\int_0^1 G\left(\frac{Y_t(i)}{Y_t}\right) di \right]$$

where $G(\cdot)$ is a real rigidity as in Kimball's (1995) state-dependent demand elasticity. This creates a kink in the demand curves of the firm. Intuitively, in a recession, firms do not find it sensible to lower prices very much since that also reduces the demand elasticity and hence does not generate more demand. Kimball aggregation may thus help to reconcile macro evidence of a low sensitivity of inflation to marginal cost in the Phillips curve (i.e. flat Phillips curve) and a micro evidence of frequent price re-optimization, which typically indicates price adjustment under one year.
Assume that Kimball aggregator is specified as in Dotsey and King (1995):

$$G\left(\frac{Y_t(i)}{Y_t}\right) = \frac{\omega}{1+\psi}\left[(1+\psi)\frac{Y_t(i)}{Y_t} - \psi\right]^{\frac{1}{\omega}} - \frac{\omega}{1+\psi} + 1$$

where $G(\cdot)$ is a strictly concave and increasing function characterized by $G(1) = 1$. The partial derivate with respect to relative output $\frac{Y_t(i)}{Y_t}$:

$$\frac{\partial G(\cdot)}{\partial \frac{Y_t(i)}{Y_t}} = \left[(1+\psi)\frac{Y_t(i)}{Y_t} - \psi\right]^{\frac{1-\omega}{\omega}}$$

Define $\phi = 1 + \lambda_f$, $\omega = \frac{\lambda_f(1+\psi)}{1+\psi\lambda_f}$, where λ_f is the net markup, ϕ is the gross markup, and ψ is the Kimball parameter that controls the degree of complementarity in firm's pricing decisions.

$$\psi = 0: \text{Dixit} - \text{Stiglitz}$$
$$\psi < 0: \text{Kimball}$$

The final good producers buy the intermediate goods on the market, package Y_t, and resell it to consumers. The final good producers minimize costs in a perfectly competitive environment and their optimization problem is

$$\min_{\left\{\frac{Y_t(i)}{Y_t}\right\}} 1 - \int_0^1 \frac{P_t(i)}{P_t}\frac{Y_t(i)}{Y_t} di$$

$$\text{s.t. } 1 = \left[\int_0^1 G\left(\frac{Y_t(i)}{Y_t}\right) di \right]$$

The first order condition is

$$\frac{Y_t(i)}{Y_t} = \frac{1}{1+\psi}\left(\left[\frac{P_t(i)}{P_t}\right]^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} \mu_{f,t}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} + \psi\right)$$

where the Lagrange multiplier (the shadow price) is $\mu_{f,t}$. Substituting $G(\cdot)$ into the Kimball aggregator and inserting to above yields

$$P_t\mu_{f,t} = \left[\int_0^1 \left[P_t(i)^{-\frac{1+\psi+\psi\lambda_f}{\lambda_f}}\right] di\right]^{-\frac{\lambda_f}{1+\psi+\psi\lambda_f}}$$

Inserting the first order condition into the zero-profit condition $P_tY_t - \int_0^1 P_t(i)\,Y_t(i)di = 0$ yields

$$\mu_{f,t} = 1+\psi-\psi\int_0^1 \frac{P_t(i)}{P_t}di$$

Notice that if $\psi = 0$ then Kimball collapses to Dixit-Stiglitz aggregation and $\frac{Y_t(i)}{Y_t} = \left[\frac{P_t(i)}{P_t}\right]^{-\frac{1+\lambda_f}{\lambda_f}}$, $P_t = \left[\int_0^1 P_t(i)^{-\frac{1}{\lambda_f}} di\right]^{-\lambda_f}$, and $\mu_{f,t} = 1$.

Intermediate Goods Producers

Technology is Cobb-Douglas

$$Y_t(i) = Z_t^{1-\alpha}L_t(i)^{1-\alpha}K_t(i)^{\alpha}$$

The log growth rate of productivity $z_t = ln\left(\frac{Z_t/Z_{t-1}}{1+\gamma}\right)$ follows $z_t = \rho_z z_{t-1} + \epsilon_{z,t}, \epsilon_{z,t} \sim \mathcal{N}\left(0, \sigma_{\epsilon_z}^2\right)$, Z_t is the level of productivity and γ is the net growth rate of productivity in steady-state. Firm's total costs:

$$TC_t(i) = W_tL_t(i) + R_t^kK_t(i)$$

Cost minimization subject to technology yields following first order conditions:

$$W_t = (1-\alpha)MC_{t,i}Z_t^{1-\alpha}L_t(i)^{-\alpha}K_t(i)^{\alpha}$$
$$R_t^k = \alpha MC_{t,i}Z_t^{1-\alpha}L_t(i)^{1-\alpha}K_t(i)^{\alpha}$$

where $MC_{t,i}$ is the firm specific marginal cost. Combining these first order conditions yields optimal capital labor ratio which after integrating over all firms ($K_t = \int K_t(i)di$ and $L_t = \int L_t(i)di$) yields a relationship between aggregate capital and labor:

$$\frac{K_t}{L_t} = \frac{\alpha}{1-\alpha}\frac{W_t}{R_t^k}$$

In the competitive equilibrium prices equal marginal costs and aggregating over all firms:

$$MC_t = MC_{t,i} = P_t(i) = \alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}W_t^{1-\alpha}\left(R_t^k\right)^{\alpha}\left(exp(z_t)(1+\gamma)\right)^{-(1-\alpha)}$$

Prices are sticky as in Calvo (1983). Each firm can readjust prices with probability $1-\zeta_p$ in each period. Firms that cannot adjust prices follow static indexing scheme in which $P_t(i)$ will increase with the steady-state rate of inflation π. The gross rate of inflation is $\Pi = 1+\pi$. The marginal utility of average household is $\Xi_{t+s}^{p} = \omega_u \beta_u^s \Xi_{t+s}^{u,p} + \omega_r \beta_r^s \Xi_{t+s}^{r,p}$, where ω_u and ω_r are the population shares , β_u^s and β_r^s are the discount factors, and $\Xi_{t+s}^{u,p}$ and $\Xi_{t+s}^{r,p}$ are the marginal utilities of the unrestricted and restricted households. Defining $\lambda_{f,t}$ as the time varying price markup shock the optimal price decision problem of the intermediate goods firm is as follows:

$$\max_{\tilde{P}_t(i)} \mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} \left[\tilde{P}_t(i)\Pi^s - \lambda_{f,t+s} MC_{t+s}\right] Y_{t+s}(i)$$

$$\text{s.t.} \quad \frac{Y_{t+s}(i)}{Y_{t+s}} = \frac{1}{1+\psi}\left(\left[\frac{\tilde{P}_t(i)\Pi^s}{P_{t+s}}\right]^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} \mu_{f,t+s}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} + \psi\right)$$

$$\ln(\lambda_{f,t}) = \rho_{\lambda_f} \ln(\lambda_{f,t}) + \epsilon_{\lambda_{f,t}}, \qquad \epsilon_{\lambda_{f,t}} \sim \mathcal{N}\left(0, \sigma_{\epsilon_{\lambda_f}}^2\right)$$

The first-order condition of this problem is:

$$\mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} \left[\frac{1+\psi+\psi\lambda_f}{(1+\psi)} \tilde{P}_t(i)\Pi^s - (1+\lambda_f)\lambda_{f,t+s} MC_{t+s}\right] \left[\frac{\tilde{P}_t(i)\Pi^s}{P_{t+s}}\right]^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} \mu_{f,t+s}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} Y_{t+s} = \mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} \frac{\psi}{(1+\psi)} \lambda_f \Pi^s \tilde{P}_t(i) Y_{t+s}$$

Defining $\frac{MC_{t+s}}{P_{t+s}} = mc_{t+s}$ and $\frac{\tilde{P}_t(i)\Pi^s}{P_{t+s}} = \frac{\Pi^s}{P_{t+s}} \frac{P_{t+s-1}}{P_{t+s-1}} \dots \frac{P_{t+1}}{P_{t+1}} P_t \frac{\tilde{P}_t(i)}{P_t} = \underbrace{\frac{\Pi^s}{\Pi_{t+s}\Pi_{t+s-1}\dots\Pi_{t+1}}}_{X_{t,s}} \underbrace{\frac{\tilde{P}_t(i)}{P_t}}_{\tilde{p}_t(i)}$

and rewriting the first order condition yields:

$$0 = \underbrace{\mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} X_{t,s}^{-\frac{1+\psi+\psi\lambda_f}{\lambda_f}} \mu_{f,t+s}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} Y_{t+s} P_{t+s}}_{f_t} \tilde{p}_t(i) - \underbrace{\frac{(1+\lambda_f)(1+\psi)}{1+\psi+\psi\lambda_f} \mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} X_{t,s}^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} \mu_{f,t+s}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} Y_{t+s} P_{t+s} \lambda_{f,t+s} mc_{t+s}}_{s_t} - \underbrace{\frac{\psi\lambda_f}{1+\psi+\psi\lambda_f} \mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \, \Xi_{t+s}^{p} X_{t,s} Y_{t+s} P_{t+s}}_{a_t} \tilde{p}_t(i)^{1+\frac{1+\lambda_f}{\lambda_f}(1+\psi)}$$

In each period, all firms that reset prices face the same problem and therefore set the same price $\tilde{p}_t(i) = \tilde{p}_t$ and hence above can be written as

$$s_t = f_t \tilde{p}_t - a_t \tilde{p}_t^{1+\frac{1+\lambda_f}{\lambda_f}(1+\psi)}$$

The average marginal utility is $\Xi^{p}_{t+s} = \sum_j \omega_j \beta_j^s \Xi^{j,p}_{t+s}$. Normalization of marginal utilities $\Xi^{j}_{t+s} = \Xi^{j,p}_{t+s} Z_{t+s} P_{t+s}$, and we write the average marginal utility as $\Xi^{p}_{t+s} = \sum_j \omega_j \beta_j^s \Xi^{j,p}_{t+s} \frac{Z_{t+s}}{Z_{t+s}} \frac{P_{t+s}}{P_{t+s}} = \sum_j \omega_j \beta_j^s \Xi^{j}_{t+s} \frac{1}{Z_{t+s} P_{t+s}}$. Define $y_{z,t+s} = \frac{Y_{t+s}}{Z_{t+s}}$. The left-hand side of above can then be expressed as:

$$s_t = \sum_j \omega_j \left\{ \frac{(1+\lambda_f)(1+\psi)}{1+\psi+\psi\lambda_f} \mathbb{E}_t \sum_{s=0}^{\infty} \zeta_p^s \beta_j^s \Xi^j_{t+s} X_{t,s}^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} \mu_{f,t+s}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} y_{z,t+s} \lambda_{f,t+s} mc_{t+s} \right\}$$

Using $X_{t,s} = \frac{\Pi^s}{\Pi_{t+s}\Pi_{t+s-1}\dots\Pi_{t+1}}$, $X_{t,0} = \frac{\Pi^0}{\Pi_t} = 1$, $X_{t+1,s-1} = \frac{\Pi^{s-1}}{\Pi_{t+1+s-1}\Pi_{t+1+s-2}\dots\Pi_{t+1+1}} = \frac{\Pi^{s-1}}{\Pi_{t+s}\Pi_{t+s-1}\dots\Pi_{t+2}}$,

$X_{t+1,s-1} \frac{\Pi}{\Pi_{t+1}} = \frac{\Pi^{s-1}\Pi}{\Pi_{t+s}\Pi_{t+s-1}\dots\Pi_{t+2}\Pi_{t+1}} = X_{t,s}$ yield a recursive formula for the term in curly brackets:

$$s_t^j = \frac{(1+\lambda_f)(1+\psi)}{1+\psi+\psi\lambda_f} \Xi_t^j \mu_{f,t}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} y_{z,t} \lambda_{f,t} mc_t + \zeta_p \beta_j \mathbb{E}_t \left(\frac{\Pi}{\Pi_{t+1}}\right)^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} s_{t+1}^j$$

Similarly, f_t and a_t terms on the right-hand side can be written in recursive formulas:

$$f_t^j = \Xi_t^j \mu_{f,t}^{\frac{1+\lambda_f}{\lambda_f}(1+\psi)} y_{z,t} + \zeta_p \beta_j \mathbb{E}_t \left(\frac{\Pi}{\Pi_{t+1}}\right)^{-\frac{1+\lambda_f}{\lambda_f}(1+\psi)} f_{t+1}^j$$

and

$$a_t^j = \frac{\psi\lambda_f}{1+\psi+\psi\lambda_f} \Xi_t^j y_{z,t} + \zeta_p \beta_j \mathbb{E}_t \left(\frac{\Pi}{\Pi_{t+1}}\right) a_{t+1}^j$$

Price Phillips Curve

Log-linearizing the first order condition yields the following Phillips curve that describes price setting:

$$
\begin{aligned}
&\left(1-\psi-\psi\lambda_f\right)\frac{\zeta_p}{1-\zeta_p}\widehat{\Pi}_t \\
&\qquad = \left(1-\psi-\psi\lambda_f\right)\sum_j \omega_j\zeta_p\beta_j\,\mathbb{E}_t\widehat{\Pi}_{t+1} + \sum_j \omega_j\left(1-\zeta_p\beta_j\right)\left(\hat{\lambda}_{f,t}+\widehat{mc}_t\right) \\
&\qquad + \sum_j \omega_j\zeta_p\beta_j\,\mathbb{E}_t\left(\hat{s}^j_{t+1} - \frac{1+\psi+\psi\lambda_f}{1+\psi}\hat{f}^j_{t+1} + \frac{\psi\lambda_f}{1+\psi}\hat{a}^j_{t+1}\right)
\end{aligned}
$$

where ⌒ refers to deviation of inflation from the steady-state, and

$$\hat{s}^j_t = \left(1-\zeta_p\beta_j\right)\left(\hat{\Xi}^j_t + \hat{y}_{z,t} + \hat{\lambda}_{f,t} + \widehat{mc}_t\right) + \zeta_p\beta_j\mathbb{E}_t\left(\frac{1+\lambda_f}{\lambda_f}(1+\psi)\widehat{\Pi}_{t+1} + \hat{s}^j_{t+1}\right)$$

$$\hat{f}^j_t = \left(1-\zeta_p\beta_j\right)\left(\hat{\Xi}^j_t + \hat{y}_{z,t}\right) + \zeta_p\beta_j\mathbb{E}_t\left(\frac{1+\lambda_f}{\lambda_f}(1+\psi)\widehat{\Pi}_{t+1} + \hat{f}^j_{t+1}\right)$$

$$\hat{a}^j_t = \left(1-\zeta_p\beta_j\right)\left(\hat{\Xi}^j_t + \hat{y}_{z,t}\right) + \zeta_p\beta_j\mathbb{E}_t\left(\hat{a}^j_{t+1} - \widehat{\Pi}_{t+1}\right)$$

In the special case where the households face no restrictions to invest in the capital markets i.e. if all households are unrestricted then the Phillips curve is simplified to

$$\widehat{\Pi}_t = \beta\mathbb{E}_t\widehat{\Pi}_{t+1} + \frac{\left(1-\zeta_p\right)\left(1-\zeta_p\beta\right)}{\zeta_p}\frac{1}{1-\psi(1+\lambda_f)}\left(\hat{\lambda}_{f,t}+\widehat{mc}_t\right)$$

Assuming further the Dixit-Stiglitz case $\psi = 0$ yields

$$\widehat{\Pi}_t = \beta\mathbb{E}_t\widehat{\Pi}_{t+1} + \frac{\left(1-\zeta_p\right)\left(1-\zeta_p\beta\right)}{\zeta_p}\left(\hat{\lambda}_{f,t}+\widehat{mc}_t\right)$$

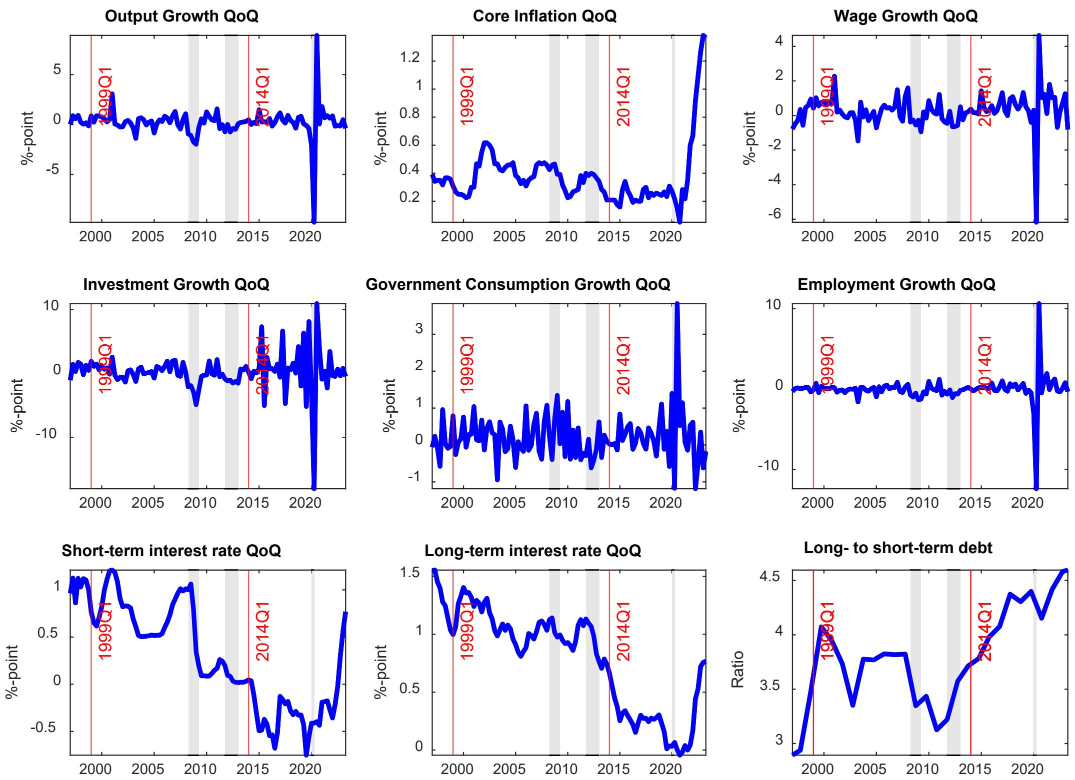
Appendix 2: Estimation Results

In this appendix we briefly describe some estimation results of the Chen et al. (2012) model with the euro area data. We estimate the Chen et al. (2012) model with Kimball price aggregation for euro area data 1999Q1-2014Q1. The data is presented in Figure *9*. The model is estimated by Bayesian methods. We show the estimation results of key parameters below in Table *1* and Table *2*. Model behavior is shown in impulse response of key shocks, historical and real time decompositions as well as in the forecast error variance decompositions below.

Data

For the observables we construct the following dataset, see Figure 9.

Figure 9 Euro Area Data 1997Q1-2023Q2 (Variables are not demeaned).



Sources: Eurostat, SDW, and Macrobond.

The blue lines show the observables. The red vertical bars show the beginning and the end of the estimation period 1999Q1-2014Q1. We choose to end the estimation period to 2014Q1 after which the policy rate went to negative territory and the APP started. The short-term policy rate is patched together with the EONIA, estimated shadow rate, and the ESTER rate. The gray bars correspond to CEPR recession dates.

Prior Choice

We calibrate the priors of annual growth rate to 2 % and inflation to 1.7 %. The prior of inflation is below the 2 % inflation target of the ECB but more consistent with the data. These priors are slightly higher than what is observed in the euro area data, but we allow rather large standard deviations for these priors. Likewise, we calibrate the prior of the term premium to one percentage point put allow for a rather large standard deviation.

The prior for the long-term to short-term debt is set to the mean of the data.

With respect to Calvo parameters we set the priors to 0.75 for wages and 0.8 prices and allow some leeway by setting the standard deviation to 0.05. These priors would effectively mean that wage contract duration is 4 quarters and equivalent price setting duration is 5 quarters. Lindé and Trabandt (2018) calibrate the Kimball complementarity parameter to be 12.2. We set the prior to slightly to lower value of 8.5 but allow for rather big standard deviation.

The rest of the priors of the parameters are based on the mean posterior estimates with the U.S. data by Chen et al. (2012).

Posterior Distribution

Regarding the priors for the shock process parameters, we choose such values that we can estimate the posterior mode which we then use in the MCMC estimation. In MCMC estimation we apply 10 chains with 125,000 draws each. To eliminate the initial value effect, we drop first 20% of draws which leaves the total sample of 1,000,000 draws on which the estimation results are based. The acceptance ratio of each chain is between 27-28%. Both univariate and multivariate convergence of parameters show stability of parameter estimates.

As in Chen et al. (2012) we find the fraction of unconstrained households is high implying that there is only weak market segmentation in data. This would imply small macroeconomic effects of asset purchases. Unless our prior hit the true value of the parameter it may be the case that this parameter is not well identified in the euro area data. The Euro area data we used ended just before meaningful asset purchases of APP and PEPP which may also contribute the high fraction of unconstrained households.

The elasticity of the risk premium to asset purchases posterior mean estimate is lower than the prior for the US data. This means that the effect of asset purchases to the risk premium and the real economy are smaller than those estimated for the US data.

The sensitivity of consumption to the interest rate are 3.6 for the unconstrained household and 2 for the restricted household at the posterior mean. Hence, these suggest that log utility specification is not sufficient and there is significant heterogeneity in the sensitivity to the interest rate for the unconstrained and restricted households. These are again very close to U.S. estimates.

The posterior means of Calvo wage parameter falls while the Calvo price parameter is close to the prior. The posterior estimate of Kimball parameter is once again close to the prior. While the price rigidities are estimated high, they are close to those obtained by Smets and Wouters (2003).

Table 1 Structural parameters.

	Prior			Posterior		
	Dist	Mean	Std Dev	Mean	95% HPD interval	
Annual growth rate	G	2.00	1	0.94	0.38	1.53
Annual inflation	G	1.70	0.5	1.59	1.14	2.05
400*((Quarterly discount factor)$^{-1}$-1)	G	0.49	0.2	0.32	0.13	0.53
Annual term premium	G	1.00	0.5	1.03	0.48	1.61
Ratio of long-term to short-term debt	G	3.60	1	1.34	1.10	1.58
Second derivative of invest adjustment costs	G	4.84	1	5.72	3.93	7.61
Second derivative of utilization adjustment costs	G	0.23	0.05	0.18	0.09	0.27
Habit	B	0.79	0.1	0.80	0.67	0.91
Inverse of Intertemporal elasticity of substitution, restricted	G	3.50	0.5	3.64	2.65	4.65
Inverse of Intertemporal elasticity of substitution, unrestricted	G	2.24	0.5	2.03	1.06	3.07
Elasticity of risk premium	G	0.38	0.1	0.26	0.14	0.40
Fraction of unrestricted	B	0.93	0.005	0.93	0.92	0.94
Ratio of marginal utilites of consumption in real terms	G	1.14	0.2	1.11	0.74	1.51
Ratio of consumption in real terms	G	1.05	0.2	0.98	0.59	1.38
Composite parameter in wage equation	B	0.56	0.05	0.60	0.50	0.70
Inverse of Frisch elasticity	G	1.97	0.2	1.85	1.50	2.22
Calvo wage parameter	B	0.75	0.05	0.60	0.52	0.68
Calvo price parameter	B	0.80	0.05	0.81	0.75	0.88
Kimball price parameter	G	8.00	4.5	9.13	2.41	16.77
Smoothing of long-term bond supply	B	0.97	0.01	0.97	0.95	0.98
Fiscal rule parameter	G	1.32	0.35	1.39	0.73	2.06
Interest rate smoothing	B	0.86	0.035	0.82	0.77	0.86
Inflation aversion of the central bank	G	1.61	0.15	2.06	1.79	2.34
Ouput growth aversion of the central bank	G	0.33	0.1	0.08	0.05	0.12

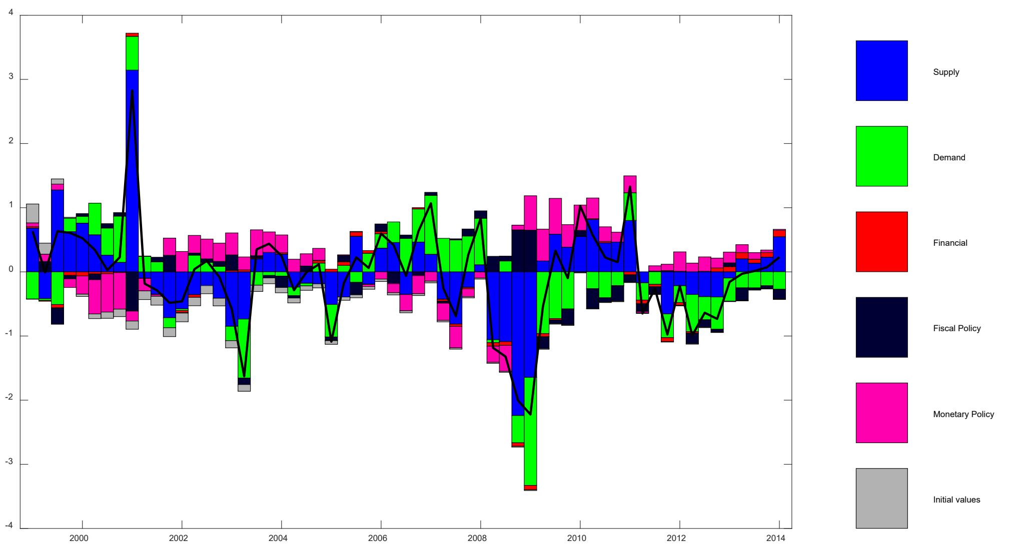
Table 2 Shock process parameters.

	Prior			Posterior		
	Dist	Mean	Std Dev	Mean	95% HPD interval	
AR(1) of productivity shock	B	0.5	0.1	0.39	0.25	0.52
AR(1) of intertemporal preference shock	B	0.5	0.1	0.31	0.16	0.47
AR(1) of leisure preference shock	B	0.5	0.1	0.35	0.21	0.50
AR(1) of price markup shock	B	0.5	0.1	0.83	0.75	0.90
AR(1) of capital adjustment cost shock	B	0.5	0.1	0.69	0.58	0.79
AR(1) of term premium shock	B	0.5	0.1	0.73	0.63	0.83
AR(1) of government spending shock	B	0.5	0.1	0.80	0.72	0.89
AR(1) of long-term bond supply shock	B	0.5	0.1	0.24	0.12	0.37
AR(1) of monetary policy shock	B	0.5	0.1	0.47	0.34	0.58
Standard deviation of productivity shock	IG	0.005	Inf	0.008	0.007	0.010
Standard deviation of intertemporal preference shock	IG	0.01	Inf	0.03	0.02	0.04
Standard deviation of leisure preference shock	IG	0.03	Inf	0.09	0.04	0.14
Standard deviation of price markup shock	IG	0.03	Inf	0.05	0.03	0.07
Standard deviation of capital adjustment cost shock	IG	0.03	Inf	0.19	0.08	0.33
Standard deviation of term premium shock	IG	0.01	Inf	0.03	0.02	0.04
Standard deviation of government spending shock	IG	0.01	Inf	0.01	0.00	0.01
Standard deviation of long-term bond supply shock	IG	0.01	Inf	0.01	0.01	0.01
Standard deviation of monetary policy shock	IG	0.003	Inf	0.0009	0.0007	0.0010

Historical and Realtime Decompositions

Using the estimated model, we first do historical shock decompositions[4]. The decomposition of output growth shows that the main driving forces of growth have been supply and demand shocks, see Figure *10*. After the global financial crisis, demand has been weak while the monetary has been supportive. Fiscal easing was important in 2009 but has then turned to fiscal tightening and contributed negatively to output growth.

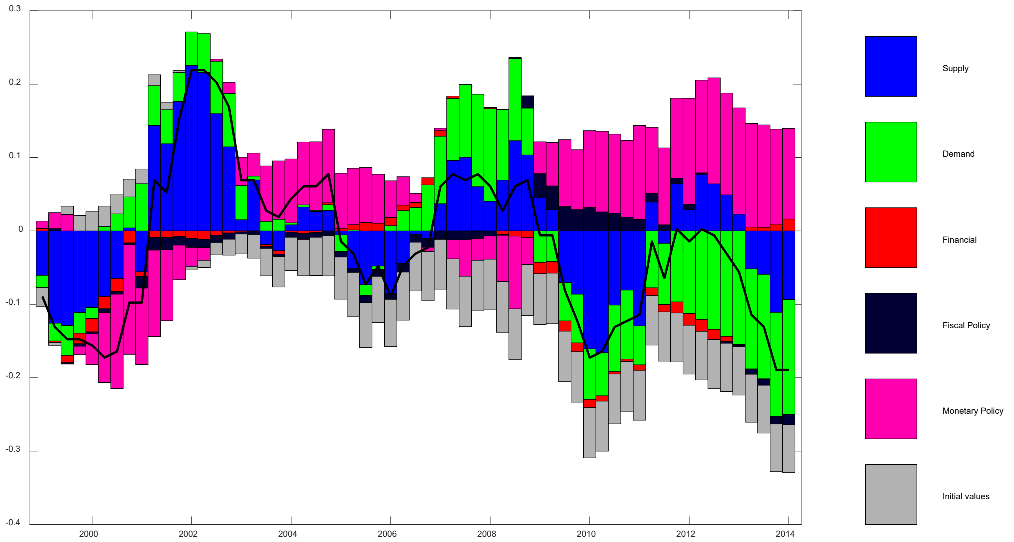
Figure 10 Decomposition of output growth in the estimation period 1999Q1-2014Q1.



The historical decomposition of inflation shows that in the global financial crisis both supply and demand shocks drove inflation down, see Figure *11*. Demand shocks turned consistently negative since 2009 while supply shocks had some positive contribution in 2012-2013. Since the beginning of the crisis monetary policy has supported inflation. Also, fiscal easing supported inflation up to 2011.

[4] We group the shocks into five categories. First, supply shock includes technology, price mark-up, and labor supply shocks. Second, demand shock includes preference and capital adjustment shocks. Third, financial shock includes the time premium and bond supply shocks. Fourth, fiscal policy shock is just the government consumption shock and fifth, monetary policy shock includes interest rate shock.

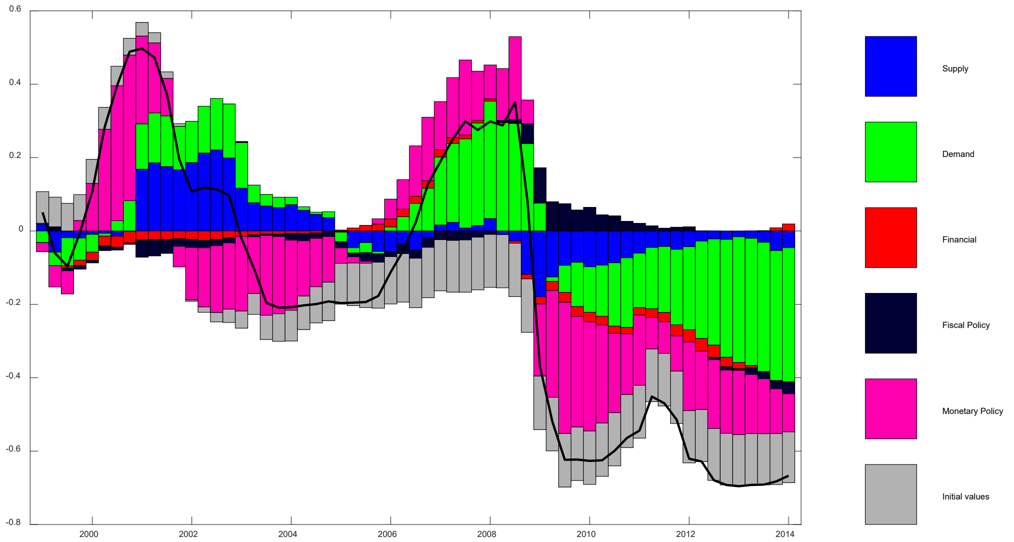
Figure 11 Decomposition of inflation in the estimation period 1999Q1-2014Q1.



The decomposition of the interest rate shows that nearly all shocks have contributed negatively to interest rates, see Figure *12*. Only fiscal easing had some positive impact on interest rate.

The initial values in the decomposition of inflation and policy rates do not fade away. This is an indication that the model is very persistent with respect to inflation and interest rate shocks. Next, we run Kalman filter to get a real time decomposition of output, inflation, and policy rates.

Figure 12 Decomposition of the policy rate in the estimation period 1999Q1-2014Q1.



Extending this shock decomposition to the whole data shows how the model behaves after the estimation period. In this after estimation period we have the interesting pandemic shock which tilts the output growth first down and then up, see Figure 13. After the initial pandemic shock, it seems that the demand has revived while the supply has had some restrictions that have contributed negatively to output growth. Monetary policy and to a lesser degree fiscal policy have contributed positively to post pandemic output growth.

Figure 13 Decomposition of output growth in the period 1999Q1-2023Q2.

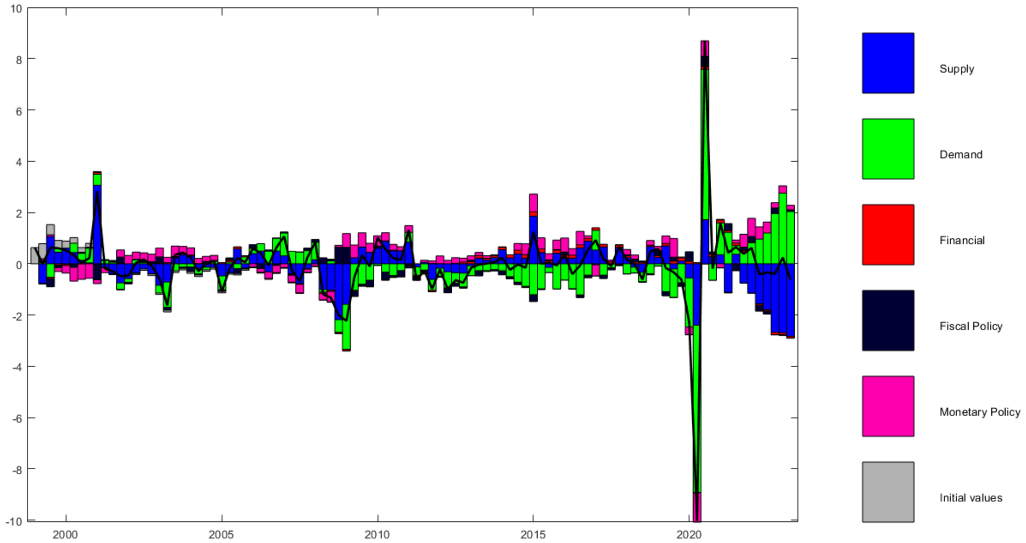
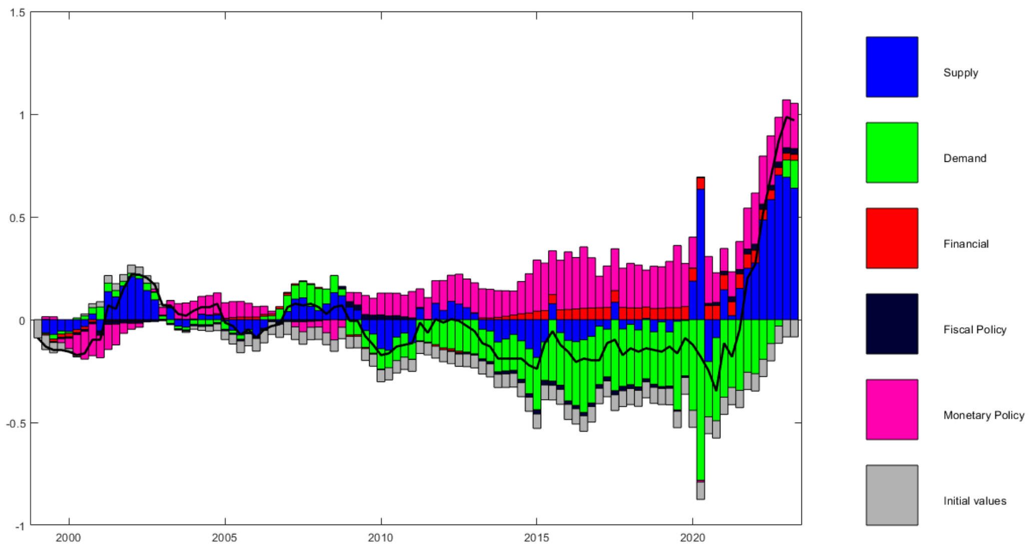


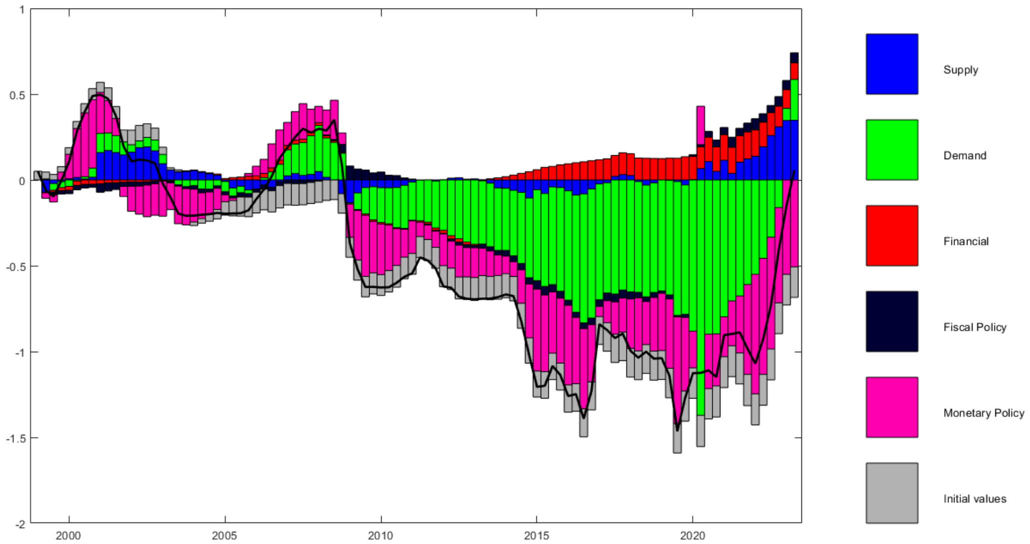
Figure 14 Decomposition of inflation in the period 1999Q1-2023Q2.



The decomposition of inflation after the estimation period also reveals interesting patterns, see Figure 14. After the pandemic peak, supply has been a main driving force of the positive inflation surprises. This supports the supply side restrictions theory emerging from both the pandemic and Russian's war in Ukraine. Demand has had a positive effect only in the last two periods in our data sample i.e. 2023Q1-2023Q2. The very accommodative and easy stance of monetary policy has supported inflation after the pandemic.

The decomposition of the interest rate after the estimation period is shown in Figure 15. This shows that the driving forces behind the recent increase in the policy rates have been supply shocks. The demand shocks have contributed positively only in 2023Q1-2023Q2. The financial shocks i.e. term premium and bond supply have also contributed positively. Fiscal policy has had only a minor positive contribution to interest rates after the pandemic.

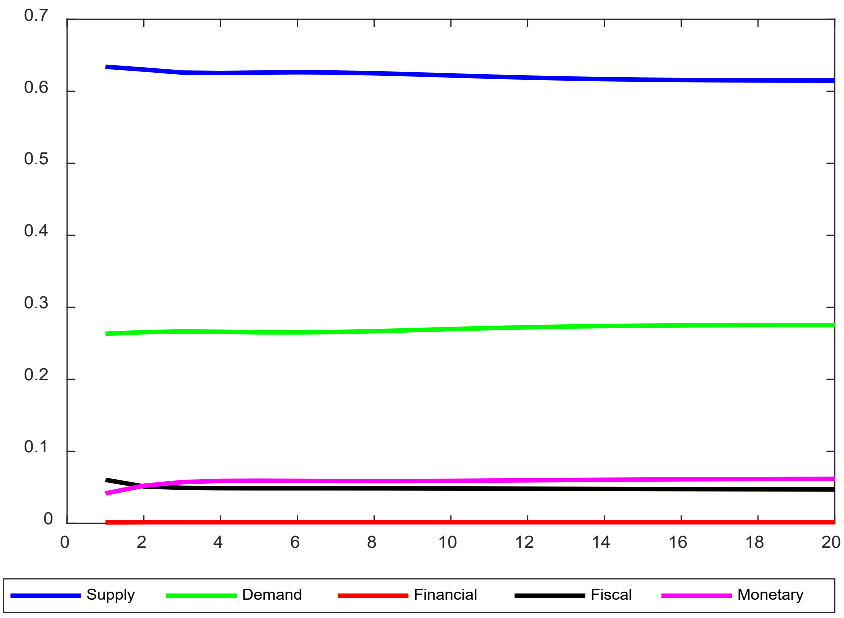
Figure 15 Decomposition of the policy rate in the period 1999Q1-2023Q2.



Forecast Error Variance Decomposition

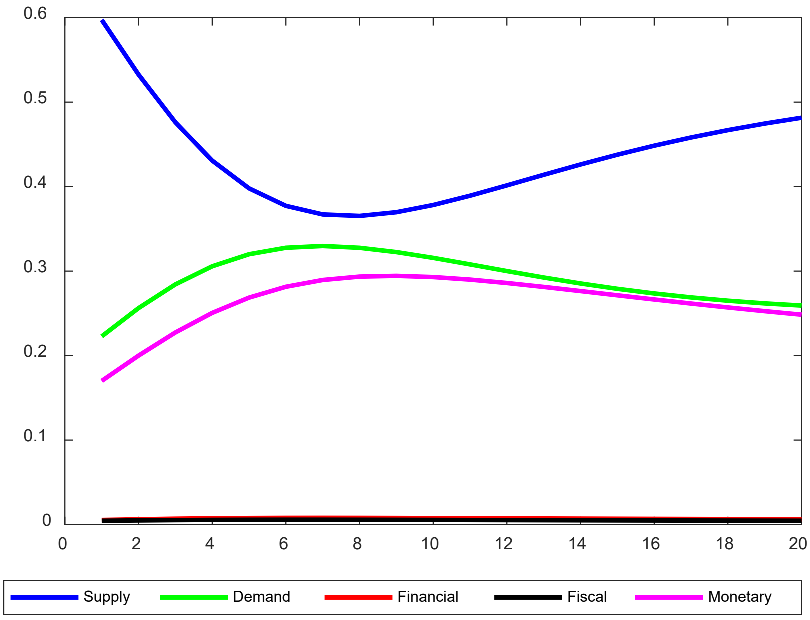
In addition to the historical and real time decompositions we also look at the forecast error variance decompositions. In Figure *16*, we show the forecast error variance decomposition (FEVD) of output. Supply shocks contribute about 2/3 of the output growth variance. A second important shock is the demand with over ¼ contribution. All other shocks are relatively unimportant to output growth variance.

Figure 16 FEVD of output.



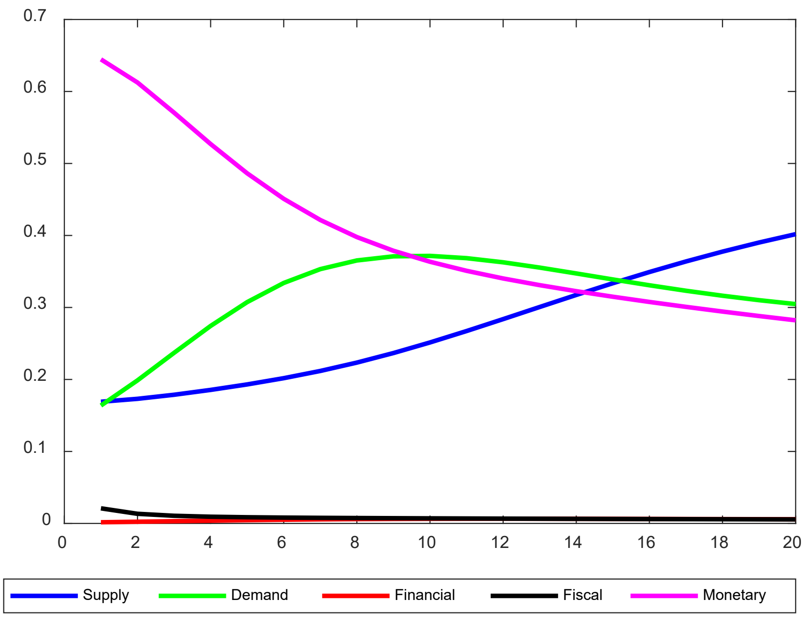
The FEVD of core inflation shows that supply shocks are most important in the short run but then lose importance as time goes by, see Figure 17. The most important of the supply shocks is the price markup shock. The demand shock and monetary policy shock explain together about half of the inflation variance.

Figure 17 FEVD of core inflation.



The forecast error variance decomposition of the interest rates is shown in Figure *18*. This shows that monetary policy shocks are the most important source of the interest rate variance in the short run but fade away as the time goes by. In the longer run both the supply and the demand shock have the most impact on the interest rate variance.

Figure 18 FEVD of policy rate



Conditional FEVD give a lot of weight on supply shocks. In below, we decompose this further in the unconditional FEVD.

VARIANCE DECOMPOSITION (in percent)

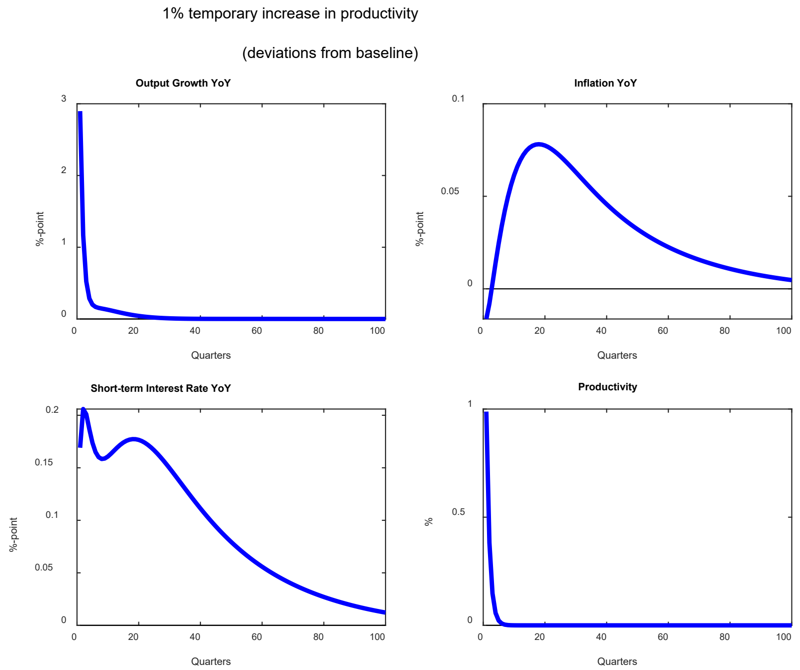
	Supply			Demand		Financial		Fiscal	Monetary
	productivity	price mark-up	labor supply	preference	capital adj.cost	time premia	bond supply		
Output	51.9	9.6	0.1	8.5	18.9	0.1	0.00	4.7	6.2
Inflation	30.1	24.4	0.9	2.2	22.7	0.5	0.04	0.3	18.9
Policy rate	44.6	8.3	0.3	1.8	25.1	0.4	0.03	0.3	19.2

Impulse response functions

To better understand the key behavior of the model we do some diagnostic simulations with shocks to supply, demand, fiscal policy, conventional and unconventional monetary policies.

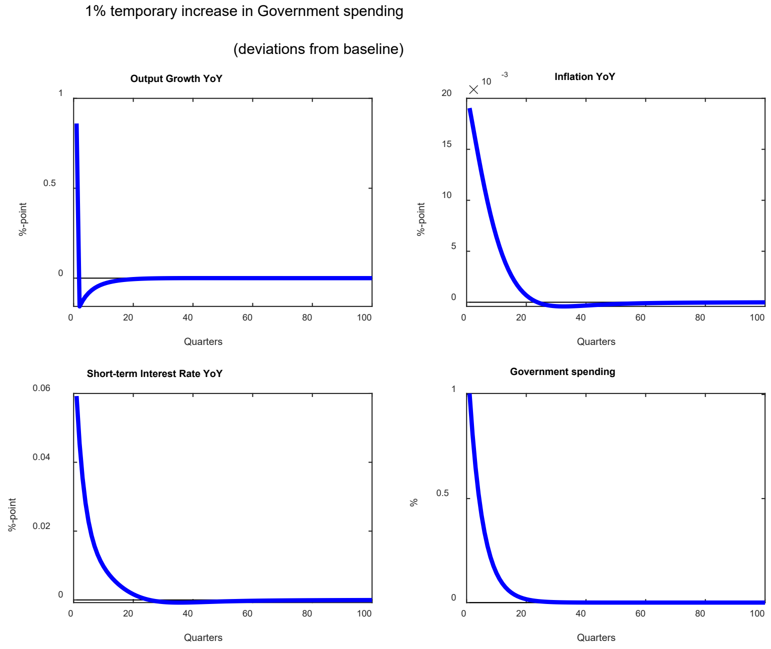
The productivity shock increases the level of productivity by one percentage point for one period and thereafter it dissipates through the estimated autoregressive process, see Figure *19*. This yields a typical supply shock feature that the annualized output increases while inflation falls. The policy rate reacts by increasing a bit in the short run. In the long run all variables return to baseline.

Figure 19 Supply shock



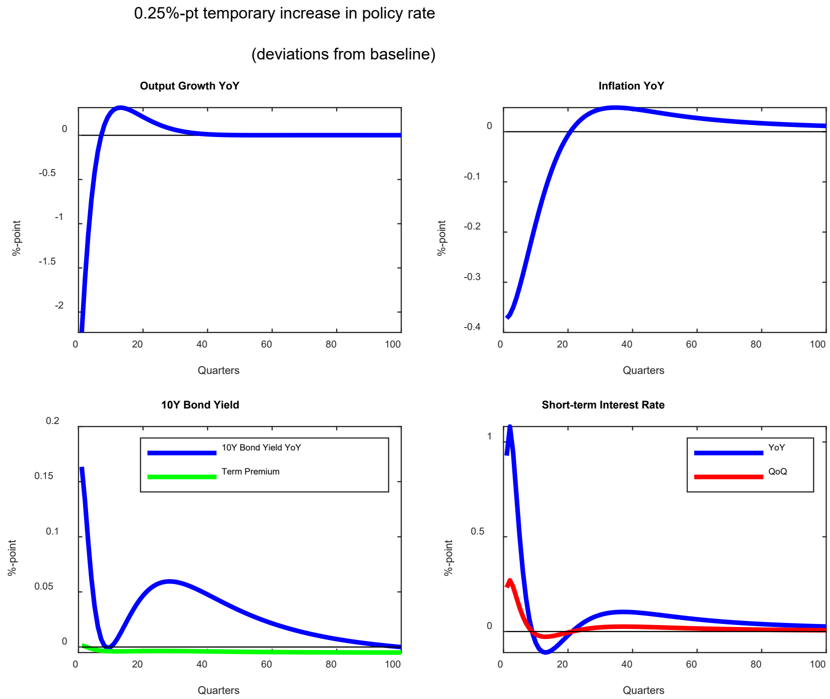
In a fiscal easing shock government expenditure is increased by one percent in the first period and thereafter it follows the estimated autoregressive process, see Figure *20*. This increases both annual output growth and inflation.

Figure 20 Fiscal easing.



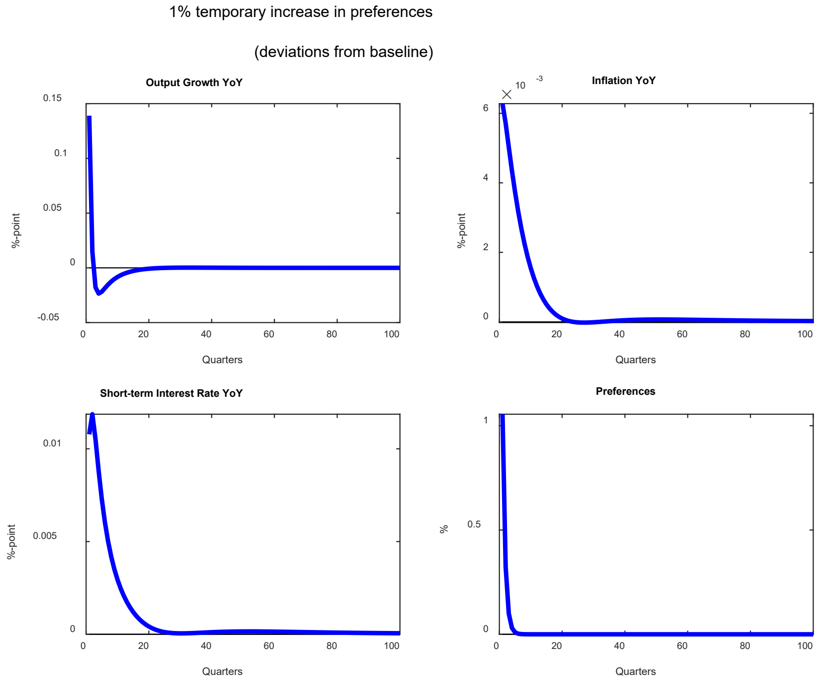
Monetary policy tightening is executed by increasing the key policy rate by 25bps for one quarter, see Figure 21. Just annualizing this would yield a one percentage point year on year shock. After the initial impact the shock process follows the estimated autoregressive pattern. A tightening of the policy rate decreases the annualized output growth and inflation.

Figure 21 Monetary policy tightening.



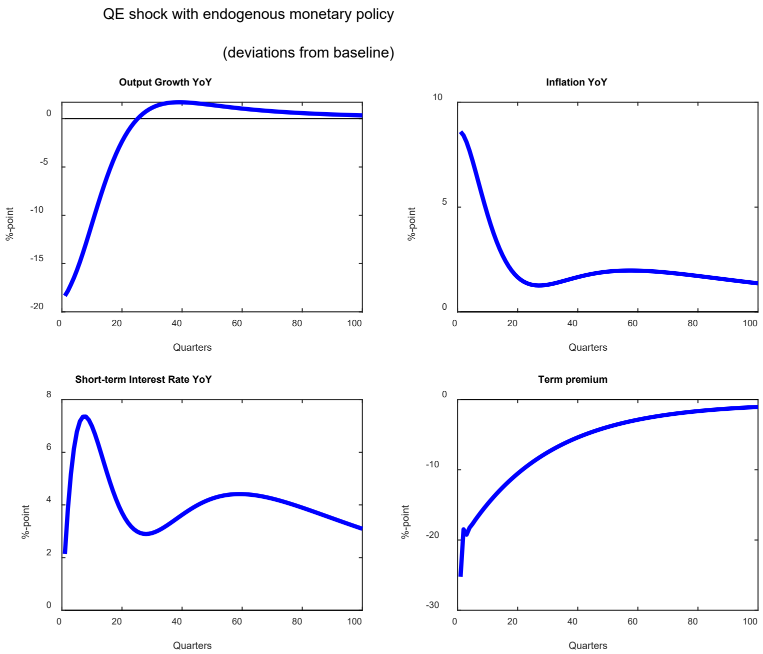
In the preference shock we increase consumption by one percent, see Figure *22*. This yields higher output growth and inflation and therefore also the policy rate increases accordingly.

Figure 22 Increase in preferences (demand shock).



In the quantitative easing shock, the bond supply is decreased i.e. central bank buys assets from the market and thus the bond prices increase and the term premium falls, see Figure *23*. This shock is calibrated to yield a 25bps fall in the term premium. While growth and inflation increase, ceteris paribus, the policy rate is also increased which decreases output growth and dampens the rise in inflation.

Figure 23 QE shock (25 bps fall in term premium).



All in all, we find the impulse responses of these shocks plausible with the estimated model.

Model comparison

We also run a model comparison between a Dixit-Stiglitz aggregation in prices and the modified Kimball aggregation in prices.

Table 3 Model comparison statistics

Model Comparison (based on Laplace approximation)

Model	**Kimball price**	**Dixit -Stiglitz**
Priors	0.5	0.5
Log Marginal Density	-89.0	-97.1
Bayes Ratio	1	0.0
Posterior Model Probability	1.00	0.0

Posterior Odds Ratio Laplace = 3427

Model Comparison (based on Modified Harmonic Mean Estimator)

Model	**Kimball price**	**Dixit -Stiglitz**
Priors	0.5	0.5
Log Marginal Density	-88.4	-96.5
Bayes Ratio	1	0.0
Posterior Model Probability	1.0	0.0

Posterior Odds Ratio Modified Harmonic Mean = 3069

Jeffreys (1961) guidance for interpreting the weight of evidence conveyed by the data for model "Kimball" against model "Dixit-Stiglitz" through posterior odds calculation is as follows:

Odds ranging from 1:1 – 3:1	"very slight evidence" in favor of model "Kimball"
Odds ranging from 3:1 – 10:1	"slight evidence" in favor of model "Kimball"
Odds ranging from 10:1 – 100:1	"strong to very strong evidence" in favor of model "Kimball"
Odds ranging from 100:1 -	"decisive evidence" in favor of model "Kimball"

Posterior odds ratio shows that the data shows strong evidence in the favor of Kimball specification. Thus, the results indicate that the Kimball specification is preferred to the Dixit-Stiglitz aggregation.

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