Forward Guidance, Quantitative Easing, or both?*

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Abstract

During the Great Recession numerous central banks have implemented various unconventional monetary policy measures. This paper aims to empirically evaluate two particular types of unconventional policies (forward guidance and quantitative easing) in a structural manner. The primary aim is to evaluate the policies jointly, to mitigate concerns that empirical evaluation of either policy in isolation is prone to at least partially absorb the effects of the other - typically simultaneously implemented - policy. The approach is structural to overcome inherent empirical difficulties in evaluating policies, e.g. in the wake of anticipation. The model is estimated for the US (1975-2015) and sheds light on the historical real effects of the government debt maturity structure as well as the contribution of Fed policy through its maturity policy during the crisis.

Keywords: Unconventional monetary policy, quantitative easing, forward guidance

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1 Introduction

The typical central bank's response to the Great Recession after running out of conventional tools has consisted of implementing multiple unconventional monetary policies, largely simultaneously. Exactly because the policies are unconventional, their effects are a priori uncertain, causing the central bank to implement numerous policies in hope some work. If the central bank finds itself in a crisis and has little appreciation for the quantitive effects of these unconventional policies, implementing multiple policies may be appropriate.

But each policy comes with potential costs. Among these costs, forward guidance involves potential credibility losses for the central bank, quantitative easing may imply risks associated with inflating the balance sheet of the central bank, and more. Because of the costs, future policy may not wish to invoke all these policies. A required input in answering the normative question "are all policies required?" is knowing the extent to which each of the unconventional policies have succeeded.

The dense sequence of policy measures complicates the evaluation of the effects of unconventional monetary policies, particularly their real macroeconomic consequences. In addition, any empirical evaluation of one unconventional policy that does not adequately control for other simultanteously implemented policies, might overestimate the true effects.

The objective of this paper is an empirical evaluation of *both* quantitative easing and forward guidance. The joint nature of the evaluation mitigates concern that one policy's evaluation appropriates the effect of the other policy. Our approach is fully structural, since unconventional monetary policies typically involve announcements ahead of policy implementation, which less structural approaches such as VARs do not cope with very well. Moreover, a structural approach also allows pinpointing the exact channel through which the policies operate.

Evaluating QE requires incorporating government debt maturity meaningfully into a model. There is ample recent evidence from event-studies showing that government debt and changes in its maturity has significant effects on asset prices (Krishnamurthy and Vissing-Jorgensen, 2014; Greenwood et al., 2015c). Additionally, novel normative considerations for the maturity composition of government debt are surfacing (e.g. Greenwood et al., 2015b). Our approach is both positive and structural. Our general approach is very much related to that of Chen et al. (2012), though we differ meaningfully in various ways: in how government bond maturity matters for the economy, in how the government decides on the maturity composition of its debt, in how the model is confronted with the data, and more. These factors combined have the general implication that we *do* find a relation between macro fluctuations and the term structure of both debt and interest rates. This has the substantive implication that QE is estimated to have significant real effects. Note that structural empirical evaluations of government maturity policy are hard to come by in their own right. To the extent they exist, the structural evaluations thus far have found very small real effects.

The paper is organised as follows. We first describe the theoretical foundations of the model in Section 2. In Section 3 we specify how that model is confronted with the data, while Section 4 documents the estimation results. Having obtained a structural empirical joint description of macro fluctuations and government bond data of different maturities, we then equip the model with features essential for policy evaluation. Section 5 incorporates anticipation and Section 6 assesses various extensions to the model. A final section summarizes results and highlights some caveats.

2 Model

We start by describing a benchmark model that forms, in our view, a required base from which one can start asking questions about maturity policy. This benchmark model has three features that differentiate it from more common NK DSGE models.

Firstly, if QE is to possibly have real effects a possible mechanism for it to operate through is required. Absent that, QE is bound to be irrelevant in the context of a NK model, as shown in Eggertson and Woodford (2003). We allow for a portfolio balance channel along the lines of Harrison (2011): the model contains a financial sector which faces an asset maturity composition decision subject to adjustment costs. The financial sector thus determines the demand for different types of government bonds.

Second, as QE policy (and Twist-type operations in particular) is essentially a decision on the supply of bonds of different maturities, the model contains a specific block accounting for its evolution. As there is relatively little structural empirical work on the maturity decision of the (consolidated) government, we investigate a range of possible maturity supply rules.

Thirdly, because any evaluation of unconventional policies necessitates a view on the evolution of interest rates of various maturities, the DSGE model better account for movements in long term interest rates. The present model can do so in two ways. On the one hand, the expectation hypothesis implies typical business cycle shocks of the type included in Smets and Wouters (2007) translate into movements of long term interest rates, as detailed in De Graeve et al. (2009). As shown in the latter, time variation in the inflation target enables reconciling the dynamics of the yield curve with a prototype NK DSGE model. On the other hand, long term interest rates can also be affected through a portfolio balance channel. The latter is captured by the aforementioned financial friction.

This section lays out these key building blocks of the model in detail. The remainder of the model is exactly that of Smets and Wouters (2007). The yield curve implications of the Smets and Wouters (2007) model are discussed in De Graeve et al. (2009). The reader is referred to those papers for additional detail.

2.1 Financial intermediary

The financial intermediary issues deposits to households paying a gross interest rate r_t^h. The intermediary then purchases a portfolio of short and long term government issued bonds paying interest r_t^S and r_t^L.

Similar to Andrés et al. (2004), Chen et al. (2012) and Harrison (2011) we follow the formulation in Woodford (2001) where long-term bonds are perpetuities that cost $p_{L,t}$ at time t and pay an exponentially decaying coupon κ^s at time $t+s+1$ where $0<\kappa\leq 1$. The advantage of this formulation is that the price in period t of a bond issued s periods ago $p_{L-s,t}$ is a function of the coupon the current price $p_{L,t}$

$$p_{L-s,t}=\kappa^s p_{L,t}. \tag{1}$$

This relation allows to express the balance sheet equation and government budget constraint (below) in a familiar form that it is easy to work with it. Furthermore, in order to keep things simple, we rule out the possibility of a secondary market for long-term bonds, meaning that agents who buy long-term debt must hold it until maturity.[1] Finally, for simplicity we assume that all government bonds issued are purchased by this intermediary.

The intermediary's balance sheet equates households' deposits to the intermediary's asset holdings of long and short term bonds:

$$b_t^h=\frac{b_t^S}{\varepsilon_t^b}+\frac{p_{L,t}b_t^L}{\varepsilon_t^b}.$$

Note that $p_{L,t}$ is the price of the long term debt in book value b_t^L. Thus, $\bar{b}_t^L=p_{L,t}b_t^L$ is the market value of long term debt holdings. As in Smets and Wouters (2007), the household balance sheet is subject to shocks ε_t^b. These drive a wedge between the return households earn on their savings and the return earned by the intermediary.

The financial firm adjusts its portfolio to maximally profit from expected interest rate differentials, but faces an adjustment cost when altering its portfolio composition. The

[1] Andrés et al. (2004) and Chen et al. (2012) discuss the advantages of these assumptions.

adjustment cost is quadratic and specified relative to a preferred steady state portfolio composition $\delta = \frac{\bar{b}^L}{b^S}$. Expected profits are

$$E_t\xi_{t+1} = \frac{r_t^S}{\pi_{t+1}} b_t^S + E_t\left\{\frac{r_{t+1}^L}{\pi_{t+1}}\frac{p_{L,t+1}}{p_{L,t}}\right\}\bar{b}_t^L - E_t\left\{\frac{r_t^h}{\pi_{t+1}}\right\}\left[\frac{b_t^S}{\varepsilon_t^b} + \frac{\bar{b}_t^L}{\varepsilon_t^b}\right] - \frac{x}{2}\left(\delta\frac{b_t^S}{\bar{b}_t^L} - 1\right)^2 \frac{1}{E_t\pi_{t+1}}.$$

The resulting FOC for short and long term bond holdings are, respectively:

$$\begin{aligned} \frac{r_t^h}{\varepsilon_t^b} &= r_t^S - x\left(\delta\frac{b_t^S}{\bar{b}_t^L} - 1\right)\frac{\delta}{\bar{b}_t^L} \\ E_t\left\{r_{t+1}^L\frac{p_{L,t+1}}{p_{L,t}}\right\} &= \frac{r_t^h}{\varepsilon_t^b} - x\left(\delta\frac{b_t^S}{\bar{b}_t^L} - 1\right)\frac{\delta b_t^S}{\left(\bar{b}_t^L\right)^2} \end{aligned}$$

In log-linearized terms the FOC can be written as

$$\begin{aligned} \hat{r}_t^S - \hat{r}_t^h &= -\chi\left(\hat{\bar{b}}_t^L - \hat{b}_t^S\right) - \hat{\varepsilon}_t^b \\ E_t\hat{r}_{t+1}^L + E_t\hat{p}_{t+1}^L - \hat{p}_t^L - \hat{r}_t^h &= \frac{\chi}{\delta}\left(\hat{\bar{b}}_t^L - \hat{b}_t^S\right) - \hat{\varepsilon}_t^b \end{aligned}$$

where $\chi = x\frac{1}{r^S b^S}$. These conditions imply that the interest rate differential the financial firm expects to earn on short term bonds increases as the volume of outstanding short term bonds increases, all else being equal. Similarly, the holding period return on long term bonds $(E_t\hat{r}_{t+1}^L + E_t\hat{p}_{t+1}^L - \hat{p}_t^L)$ will exceed the interest rate paid to households $\hat{r}_t^h$ when the value of outstanding long term bonds is high relative to short term bonds. Thus, relative asset returns are a function of relative amounts outstanding, a key tenet of preferred habitat-style models (e.g. Andrés et al., 2004; Vayanos and Vila, 2009).

An alternative way to read the first order conditions is shown in equations (2) and (3). First, the interest rate households face in making consumption decisions is an average of the long and short term returns:

$$\hat{r}_t^h = \frac{\delta}{1+\delta}\left[E_t\hat{r}_{t+1}^L + E_t\hat{p}_{t+1}^L - \hat{p}_t^L\right] + \frac{1}{1+\delta}\hat{r}_t^S + \hat{\varepsilon}_t^b. \tag{2}$$

Second, the spread between long term and short term rates is a function not only of the expectation hypothesis (as in more standard NK DSGE models), but also depends on relative asset quantities demanded by the financial sector:

$$\left[E_t\hat{r}^L_{t+1} + E_t\hat{p}^L_{t+1} - \hat{p}^L_t\right] = \hat{r}^S_t + \frac{1+\delta}{\delta}\chi\left(\widehat{\bar{b}^L_t} - \hat{b}^S_t\right). \tag{3}$$

Note that the risk premium shock $\hat{\varepsilon}^b_t$ of Smets and Wouters (2007) does not directly impact the spread between long and short returns; a direct consequence of it entering the balance sheet symmetrically, affecting long and short bond holdings alike. It therefore is possible to interpret it as Fisher (2015) advocates, as a shock that increases the preference for (safe/liquid) Treasury assets, irrespective of their maturity.

These optimizing conditions pin down the demand for bonds of different maturities. Let us now turn to how the supply of government bonds is determined.

2.2 Government

The government budget constraint is given by

$$\begin{aligned} b^S_t + p_{L,t}b^L_t + T_t &= \frac{r^S_{t-1}}{\pi_t}b^S_{t-1} + \frac{r^L_t}{\pi_t}p_{L,t}b^L_{t-1} + G_t \\ b^S_t + \bar{b}^L_t + T_t &= \frac{r^S_{t-1}}{\pi_t}b^S_{t-1} + \frac{r^L_t}{\pi_t}\frac{p_{L,t}}{p_{L,t-1}}\bar{b}^L_{t-1} + G_t \end{aligned}$$

Thus, the government issues two types of debt (short and long term) to finance the deficit $(G_t - T_t)$ and pay interest on existing debt. Taxes levied are a function of the total amount of debt (with $\theta > 0$), thus ensuring debt remains stable.

$$T_t = \Theta\left(\frac{b^S_{t-1} + \bar{b}^L_{t-1}}{b^S + \bar{b}^L}\right)^\theta \varepsilon^{TD}_t \tag{4}$$

We allow for there to be shocks ε^{TD}_t to total debt, which in standard NK DSGE models act as lump sum transfers, with no real dynamic effects. If, in response to these debt shocks, the maturity composition of debt supply remains constant (at market value), then there is no cause for the financial sector to adjust its maturity balance. As a result, changes in the level of debt that leave the maturity composition unaffected have no real effects also in a model with portfolio balance effects.

Government spending features both an exogenous component g_t and an endogenous response to the economy.

$$G_t = g_t(y_t)^{\vartheta} \tag{5}$$

The above equations stipulate how total government debt evolves, but do not pin down the composition of debt. Pinning down the determinants of maturity composition is far from trivial, both from a normative and a positive perspective, as is clear from e.g. Greenwood et al. (2015b) and Hall and Sargent (2011). Our analysis starts from the following specificiation:

$$\frac{b_t^L}{b_t^S} = \zeta \varepsilon_t^{MAT} \left(\varepsilon_t^{TD}\right)^{\nu}. \tag{6}$$

This specification says that, in the absence of shocks ε_t^{MAT} and ε_t^{TD}, the government aims to keep the maturity of government debt constant (and equal to ζ). Note that the maturity target here is specified in terms of book value, b_t^L. The motivation for this relatively simple maturity supply rule lies in the following considerations. First, from a positive perspective, it is not obvious how the Treasury actually decides on the maturity structure of its debt. As such, a constant composition seems as good starting point as another. Relatedly, also from a normative perspective it is not entirely clear how maturity structure should be determined, as there are different potential objectives the government may wish to pursue (e.g. cost minimization, risk management, demand stimulus, financial stability; see Greenwood et al. (2015b) for an extensive discussion). In later specifications we extend the constant maturity benchmark case and consider the effects of incorporating endogenous policy choices. Second, Treasury reports debt in book rather than market values, which motivates our choice for a rule specified in book rather than market values. In addition, while the government has relatively direct control over the book value, it has less so over the market value. Third, as has become particularly apparent in the Great Recession, the Treasury is not the only actor affecting the maturity of outstanding public debt. The central bank's quantitative policies equally affect the consolidated government's balance sheet and its maturity composition. As described in Greenwood et al. (2015a) these actions have not always been well coordinated.

Note that if the government would keep the market value composition of debt constant, typical business cycle shocks would leave the portfolio balance effect on interest rates inactive. Their transmission would then be the same as it is in a prototype NK DSGE model.[2]

The maturity-supply rule (6) also incorporates two shocks. Let us consider each in turn. First, ε_t^{MAT} is an exogenous shock that alters the maturity composition of the government debt. A positive realisation of this shock implies an increase in the maturity of government debt. By and large, this shock leaves the total level of debt unchanged. Particularly, note that the shock does not appear directly in any other part of the model. However, the shock may have an effect on the price of long term debt, and thus influence the market value of debt. For any of the estimated parameter constellations, the effect on total debt turns out to be relatively small.

Second, we allow the shock ε_t^{TD} to possibly affect the maturity composition. The degree to which this happens is measured by ν. If, for instance, ν is negative, this means that an exogenous increase in the level of debt is primarily financed through short term, rather than through long term debt. Alternatively, some restructuring of government debt maturity may actually go hand in hand with a change in the absolute level of debt.

It is worth pointing out that our fiscal block differs substantially from that in e.g. Chen et al. (2012) and most other DSGE models with bonds of different maturities. There, the supply of long term bonds is specified as an exogenous process. Our specification, by contrast, treats bonds of different maturities symmetrically. Debt stabilization is a function of total debt, rather than a single maturity component of total debt. Our analysis brings the demand and supply implications of maturity policy to the fore. In much of the related literature, the debt level and maturity model choices are somewhat in the background and their implications not necessarily easy to appreciate.[3]

[2] As an empirical matter, within the confines of the present model and data, it turns out that a maturity supply rule in terms of book value far outperforms one that aims to stabilize the market value.

[3] The model economy features a significant role for debt and maturity fluctuations in an active monetary,

2.3 Monetary policy

The central bank follows a nominal interest rate rule by adjusting its instrument in response to deviations of inflation and output from their respective target levels. The (linearized) monetary policy reaction function is exactly the same as that of Smets and Wouters (2003) or De Graeve et al. (2009):

$$\begin{aligned}\hat{r}_t^S &= \rho_R \hat{r}_{t-1}^S + (1-\rho_R)\widehat{\overline{\pi}}_t + \rho_R(\widehat{\overline{\pi}}_t - \widehat{\overline{\pi}}_{t-1}) \\ &\quad + (1-\rho_R)(r_\pi(\widehat{\pi}_t - \widehat{\overline{\pi}}_t) + r_y(\widehat{y}_t - \widehat{y}_t^{flex})) \\ &\quad + r_{\Delta y}(\widehat{y}_t - \widehat{y}_{t-1} - (\widehat{y}_t^{flex} - \widehat{y}_{t-1}^{flex})) + \hat{\varepsilon}_t^r. \end{aligned} \tag{7}$$

The monetary authority follows a generalized Taylor rule by gradually adjusting the policy-controlled interest rate ($\hat{r}_t^S$) in response to inflation and the output gap, defined as the difference between actual and potential output (Taylor, 1993). Consistently with the DSGE model, potential output is defined as the level of output that would prevail under flexible prices and wages in the absence of wage and price mark-up shocks.[4] The inflation target is subject to *iid*-Normal shocks and assumed to have the following general form: $\Delta\widehat{\overline{\pi}}_t = \rho_{\overline{\pi}}\Delta\widehat{\overline{\pi}}_{t-1} + \epsilon_t^{\overline{\pi}}$. When $\rho_{\overline{\pi}}$ is zero the inflation target reduces to a random walk. Positive values of $\rho_{\overline{\pi}}$ imply smoother changes in the target. In addition, there is also a short-run feedback from the change in the output gap. The parameter ρ_R captures the degree of interest rate smoothing. Finally, we assume that the monetary policy shock ($\hat{\varepsilon}_t^r$) follows a first-order autoregressive process with an *iid*-Normal error term: $\hat{\varepsilon}_t^r = \rho_r \hat{\varepsilon}_{t-1}^r + \epsilon_t^r$.

Let us summarize the key novel elements of the model. Interest rates of different maturities affect real decisions. The term structure of interest rates is determined by both

passive fiscal environment, using the terminology adopted by Leeper (1991). Alternative monetary/fiscal policy constellations can induce additional mechanisms through which maturity can affect the economy, via the fiscal theory of the price level (e.g. Cochrane, 2011).

[4] This follows the approach in Smets and Wouters (2007) closely. Note that our specification of the flexible price economy counterpart does not feature the portfolio adjustment costs either, thus rendering real effects of the maturity composition absent in the output target of the central bank.

the expectations hypothesis and a portfolio balance channel. The *absolute* supply of government bonds is determined by the debt accumulation equation. The *relative* supply of bonds of different maturities is governed by the maturity supply-rule. These model-blocks are incorporated in the model of Smets and Wouters (2007).

3 Mapping the model to the data

3.1 Observation equation and data

Our choice of observables and specification of the observation equation extends that of Chen et al. (2012) in various ways. Like them, we directly observe the long term-interest rate (the 10-year Treasury constant maturity yield). Differently however, we observe the quantity of both long and short bonds separately (while Chen et al. (2012) observe only the ratio of the two). The observation equations for these model variables are

$$\begin{aligned} r_t^{L,obs} &= c^{r^L} + \hat{r}_t^L \\ \Delta b_t^{S,obs} &= c^b + \left(\hat{b}_t^S - \hat{b}_{t-1}^S\right) \\ \Delta b_t^{L,obs} &= c^b + \left(\hat{b}_t^L - \hat{b}_{t-1}^L\right). \end{aligned}$$

Among other things, this specification allows distinguishing between changes in the level of debt which may have maturity implications and mere maturity changes at constant levels of debt. The debt data is constructed following Chen et al. (2012) closely.[5] Our data extends the sample of Chen et al. (2012) and covers the period 1975:Q2-2015:Q3. Figure 1 describes the evolution of the consolidated government debt data split across maturity, where short term debt is all liabilities with maturity up to one year, and long term captures everything longer. Note from the above observation equation that the constant in the two

[5]Note however that the present model equates the long term debt data to the book value of debt $\hat{b}_t^L$, while they equate it to market values. The original source of the data is the Treasury, which reports debt at book value.

debt equations is the same. Thus, both debt variables grow at the same rate, leaving all fluctuations in maturity explained within the model.[6] We add these observables to the data investigated by Smets and Wouters (2007), which ensures that alternative business cycle shocks are well-identified. Our benchmark model specification has as many shocks as observables: compared to Smets and Wouters (2007) the model contains three additional observables ($r_t^{L,obs}, \Delta b_t^{S,obs}, \Delta b_t^{L,obs}$) and three additional shocks ($\varepsilon_t^{\bar{\pi}}, \varepsilon_t^{TD}, \varepsilon_t^{MAT}$).

3.2 Functional forms

The shock processes that are novel to Smets and Wouters (2007) and De Graeve et al. (2009) are potentially persistent:

$$\begin{aligned} \varepsilon_t^{TD} &= \rho_{TD}\varepsilon_{t-1}^{TD} + u_t^{TD} \\ \varepsilon_t^{MAT} &= \rho_{MAT}\varepsilon_{t-1}^{MAT} + u_t^{MAT}. \end{aligned}$$

In confronting different versions of the model with the data, maturity shocks are invariably found to be extremely persistent. In light of that, in what follows we simply set $\rho_{MAT} = 0.999$. Thus, effectively, maturity shocks are permanent.

The theoretical exposition assumes maturity adjustment costs to be quadratic in the *level* of the maturity composition. However, a priori it is unclear what functional form the adjustment costs take. As an analogue, consider adjustment costs to changing capital. While many early DSGE models assumed adjustment costs to changing the level of capital, empirical analysis has often found dynamic adjustment costs more plausible, where changing the level of investment rather than capital determines the cost (e.g. Christiano et al., 2005; Smets and Wouters, 2007). In light of this, we allow for a flexible form for maturity

[6] The debt variables in the model grow at the economy's deterministic growth rate, γ.

adjustment costs, which embeds both static and dynamic costs. Specifically, we estimate

$$\begin{aligned}\hat{r}_t^S - \hat{r}_t^h &= -\chi\left(\overset{\wedge}{\bar{b}}{}_t^L - \hat{b}_t^S - \rho_\chi\left[\overset{\wedge}{\bar{b}}{}_{t-1}^L - \hat{b}_{t-1}^S\right]\right) - \hat{\varepsilon}_t^b \\ E_t\hat{r}_{t+1}^L + E_t\hat{p}_{t+1}^L - \hat{p}_t^L - \hat{r}_t^h &= \frac{\chi}{\delta}\left(\overset{\wedge}{\bar{b}}{}_t^L - \hat{b}_t^S - \rho_\chi\left[\overset{\wedge}{\bar{b}}{}_{t-1}^L - \hat{b}_{t-1}^S\right]\right) - \hat{\varepsilon}_t^b.\end{aligned}$$

This specification encompasses two extremes: when $\rho_\chi = 0$ adjustment costs are static, or determined by the ratio of long to short term debt. Alternatively, when $\rho_\chi = 1$ adjustment costs are dynamic and driven by changes in the maturity composition.

3.3 Priors

The prior for 100χ is Normal with mean 5 and standard deviation of 1. Our prior covers middle ground between two prior DSGE studies. First, the prior mean is half that of Harrison (2011), who calibrates the elasticity at 0.1. Our prior mean is high relative to that of Chen et al. (2012), though the structural parameter is not entirely the same, given the different structure of the model.[7] Our specification of maturity adjustment costs nests both static and dynamic adjustment costs: ρ_χ has a relatively flat Beta prior. The parameter $\delta = \frac{\bar{b}^L}{b^S}$ is fairly well pinned down by the data, so we give it a farily tight prior. The prior mean for the common growth rate c^b is the average of the growth rates of long and short term debt, with a standard deviation that comprises the individual growth rates. The prior for ν is centered around zero, since both positive and negative values are plausible. The prior for θ encompasses both slow and rapid repayment of total debt. The prior distributions for the remaining parameters are those of Smets and Wouters (2007) and De Graeve et al. (2009).

[7] Specifically, in the present model the parameter χ controls not merely the elasticity of the term spread to bond supply, but equally its impact on the real economy. In the model of Chen et al. (2012), the real effects are controlled by a separate parameter, which is the degree of market segmentation.

4 A benchmark DSGE model with a role for maturity

We first describe an estimate of the benchmark model, without anticipation, and with a relatively simple maturity supply rule for government debt. This benchmark highlights how the model captures the data, and how important the shocks and frictions are to do so.

Parameter estimates. The estimated structural parameters are contained in Table 1. A number of features stand out from these estimates. Let us start with the maturity friction itself, or the financial block. The parameter estimate for 100χ is somewhat lower than the prior mean and not particularly precise, at 4.53 with a standard deviation of 0.88. This parameter controls the elasticity of the spread to movements in debt maturity, and thereby also its real effects. Despite the imprecision, our estimate differs quite substantially from that in Chen et al. (2012). Particularly, the latter find posterior estimates that strongly push both the interest rate elasticity and the real effects of changes in debt maturity toward zero. This difference in results is a consequence of a combination of factors. First, by observing both short and long term debt separately, debt variables receive a larger weight in the likelihood. Second, the long term interest rate in our model is already well fitted independently of the maturity friction. This follows largely from allowing changes in the inflation target over time, as detailed in De Graeve et al. (2009). Absent that, since traditional business cycle shocks cannot explain movements in long term rates, the maturity of debt is required to solely explain long rates - the comovement between the two does not seem particularly apparent in the data. Third, the posterior estimates appear to suggest a maturity friction that is a function of the change in maturity is much preferred over one in the level of maturity, since ρ_χ is estimated close to 1. Fourth, the treatment of the fiscal block is quite different and arguably more flexible in the present setting. Overal, the fact that the friction through which debt maturity affects interest rates and the real economy, allows QE to potentially generate more substantial effects.

Regarding the fiscal block, both debt and maturity shocks are active. Their estimated variance is high, which is no surprise given the large fluctuations in debt witnessed in Figure 1. These fluctuations take place around an estimated common growth rate c^b of 2.49%. The parameter ν is estimated negative at -0.42, which implies that exogenous increases in debt tend to be financed in first instance by increases in short term debt.

How the model captures the data. Figure 2 contains information about how the estimation characterizes the debt data. The bold line in the first panel shows the evolution of $\hat{b}_t^L$ around the constant debt growth rate c^b. Similarly, the bold line in the second panel plots $\hat{b}_t^S$ around the (common) constant debt growth rate c^b. The third panel plots the difference between the two, i.e. the evolution of the maturity composition of the debt.

The dashed (resp. dotted) line in the upper three panels shows the contribution of maturity (resp. debt) shocks to the respective debt variables. The bottom two panels show the shock processes underlying these contributions. A number of observations stand out. First, the bulk of fluctuations in the maturity composition of debt are explained by ε_t^{MAT}. This shock captures both the catch-up of long term debt to the level of short debt in first decade of the sample, as well as the swings in maturity observed during the Great Recession. Both these phenomena are essential features of the debt data, as is apparent from Figure 1 (top panel). These maturity shocks have a relatively small impact on the total level of debt. Second, debt shocks ε_t^{TD} are essential in capturing the fast runup in debt (of all maturity) witnessed during the crisis. The ε_t^{TD}-process is persistently positive in the last years of the sample. These debt shocks explain a small fraction of movements in maturity. Summing up, the benchmark model describes a coherent framework in which macroeconomic fluctuations are tied to the term structure of debt and interest rates. The joint explanation of macro variables, the term structure and debt variables stands in contrast to other evaluations of QE. In Chen et al. (2012), for instance, structural estimation seems to choose parameter constellations that disconnect maturity fluctuations from macro variables.

Impulse response functions We now shed further light on dynamics of maturity and their interplay with the real economy. Figure 3 shows that a permanent compositional shift of bonds toward shorter maturities implies a long lasting reduction in the yield spread. The yield spread falls on impact as the supply of long maturity bonds falls relative to short bonds. The interest rate that determines consumption, r_t^h, drops on impact, thus generating an increase in output and inflation. Note that the long term interest rate rises after its initial drop. This as a result of two forces. Firstly, the estimated parameter $\rho_\chi = 0.98$ reveals that adjustment costs are almost entirely dynamic, which causes the permanent change in maturity to affect the spread (almost) only temporarily. Secondly, the economic boom causes the central bank to increase the policy rate persistently, which feeds into the long term interest rate through a standard expectations channel. Note that a quantitatively significant permanent switch in maturity (2% of the stock of debt in hands of the public) implies a reduction of the yield spread of about 8 basis points (in annual terms). The resulting economic expansion is relatively small, at an increase in output of almost .05 percent. (For comparison purposes, the peak output effect of a one standard deviation monetary policy shock is .5)

Figure 4 details the effects of a debt shock ε_t^{TD}. A one standard deviation innovation amounts to a (peak) increase in debt of 4%. While debt of all maturities increases, the rise in short term bonds outpaces that of long term bonds. Perhaps surprisingly, on impact the price of long term bonds rises following the increase in total debt. Thus, while absolute supply of bonds of all maturities increases, the relative supply of long term bonds (slightly) decreases, causing the relative price of long term bonds to rise. The subsequent periods are characterized by a catch-up of long term debt, as the government debt maturity composition gradually returns to equilibrium.

5 Anticipation

The baseline model enables identifying the real effects of fluctuations in maturity. Thus far, fluctuations in maturity themselves are exogenous, driven mostly by maturity shocks ε_t^{MAT} and marginally affected by debt shocks ε_t^{TD}. Starting from a structural model that adequately describes the macro, term structure and debt data jointly, we now add several elements to the model that enable it to evaluate unconventional monetary policy. We start with a study of the effect of anticipation.

Unconventional monetary policy is intimately tied to anticipation. The central bank announces what actions it will pursue in the future in hope of stimulating the economy today. Forward guidance is communication about the policy rate in the future. Quantitative easing is typically announced up front, and laid out as a plan of successive policy implementations. While the anticipated nature of forward guidance is typically recognized, this is far less the case for QE.[8] We here extend the model to account for anticipation effects.

Forward guidance is captured by extending the central bank's policy rule to contain anticipated policy shocks. Thus, the central bank is able to convey to the public that interest rates will be lower in the future than its usual policy rule would dictate. This follows the approach laid out in, e.g., Campbell et al. (2012) and Del Negro et al. (2013). The interest rate policy rule then becomes

$$\begin{aligned}
\hat{r}_t^S &= \rho_R \hat{r}_{t-1}^S + (1-\rho_R)\widehat{\bar{\pi}}_t + \rho_R(\widehat{\bar{\pi}}_t - \widehat{\bar{\pi}}_{t-1}) \\
&\quad + (1-\rho_R)(r_\pi(\widehat{\pi}_t - \widehat{\bar{\pi}}_t) + r_y(\widehat{y}_t - \widehat{y}_t^{flex})) \\
&\quad + r_{\Delta y}(\widehat{y}_t - \widehat{y}_{t-1} - (\widehat{y}_t^{flex} - \widehat{y}_{t-1}^{flex})) + \hat{\varepsilon}_t^r + \sum_{n=1}^{N} \hat{\varepsilon}_{t-n}^r \qquad (8)
\end{aligned}$$

where n denotes the anticipation horizon, where a shock at horizon n has its own variance σ_{-n}^r.

In similar fashion, we extend the maturity supply rule to encompass anticipated shocks.

[8] With the notable exception of Greenwood et al. (2015c).

While fiscal policy is often argued to have anticipated effects in general, unconventional monetary policy that operates on maturity is often explicitly pre-announced. We write the (linearized) maturity policy rule in the model with anticipation as

$$\hat{b}_t^L - \hat{b}_t^S = \hat{\varepsilon}_t^{MAT} + \sum_{n=1}^{N} \hat{\varepsilon}_{t-n}^{MAT} + \nu \hat{\varepsilon}_t^{TD}.$$

For each of the anticipated shocks, we maintain the same persistence properties as in the benchmark model. That is, anticipated monetary policy shocks are *iid*, while anticipated maturity shocks are permanent. The exact timing and specification of anticipation effects is not clear-cut a priori. Different authors adopt different approaches: satiate all horizons up to a certain length (e.g. Del Negro et al., 2013), a single horizon (e.g. De Graeve and Queijo von Heideken, 2015), or certain intermediate horizons (e.g. Schmitt-Grohé and Uribe, 2012). We have experimented with various specifications and horizons. Overall we find 1) anticipation to be relevant in both interest rate and maturity shocks,[9] and 2) the exact horizon at which the posterior is maximized is not always pinned down exactly, but hovers around four quarters depending on the exact specification. Specifically, interest rate anticipation starts to matter only at horizons $n \geqslant 4$ quarters. Anticipation in maturity shocks vastly reduces the role of unanticipated maturity shocks, possibly even entirely.

We here present the results for a particularly parsimoneous specification that features anticipation four quarters ahead and at no other horizons. Overall, a model with anticipation (Marginal Likelihood:-1698.98) is preferred to a model without (ML:-1703.22). Because of this better performance, we continue working with the model with anticipation. In the model with anticipation, the maturity friction is estimated to be more important ($100\chi = 5.16$) compared to the benchmark model. We now use that model to quantify the effect of unconventional monetary policy.

[9] Estimation of model variants that allow for anticipation in debt shocks do not attribute a large role to such anticipation.

5.1 The effects of "Operation Twist 1"

In September 2011 the Fed announced it would change the maturity of its balance sheet: buying $400 billion in long term bonds and selling the same amount in short term bonds by the end of June 2012.[10] This section evaluates the real effects of that policy through the lens of the model.

The model is estimated on data that pertains to debt in hands of the public. Both the central bank and the treasury influence the maturity of bonds outstanding. Hence, to evaluate the impact of Operation Twist, it is not sufficient to merely inspect the time series of the maturity shock, or its contribution to macro fluctuations.

Figure 5 shows the effect of the anticipated maturity shock scaled to the size of Operation Twist 1. The top row shows the policy: the Fed announces to buy $400 billion long term bonds (approximately 7% of the stock outstanding in 2011:Q3), thus reducing the expected amount of long term bonds (b^L) outstanding.[11] The counterpart of that sale is an increase in short terms bonds (b^S) available to the public. Long term rates drop by 6 basis points on the day of the announcement and reach a peak effect of just over 12 basis points at the time of the policy implementation. The policy generates an economic expansion with a peak effect on output of 0.6%. Quantitatively, this is just slightly larger than the output response that the central bank generates after traditional, unanticipated policy shocks (of one standard deviation in size). The policy rate response in Figure 5 is not particularly realistic, as the Fed at no point during "Operation Twist 1" considered increasing policy rates. In the model, the policy rate increase arises naturally as the policy rule leans against the economic expansion that the maturity shift causes. While Chen et al. (2012) and Gertler and Karadi (2013)

[10] Specifically, on 21 September 2011, the Fed announced "... the Committee decided today to extend the average maturity of its holdings of securities. The Committee intends to purchase, by the end of June 2012, $400 billion of Treasury securities with remaining maturities of 6 years to 30 years and to sell an equal amount of Treasury securities with remaining maturities of 3 years or less".

[11] Note that the policy experiment is conducted in market value, as in the Fed announcement.

superimpose a zero interest rate response in their evaluation, we refrain from doing so as our interest lies in separating the effect of the two policies. Perhaps remarkably, we find significant real effects of QE even without imposing the policy rule to stay inactive for the first year of the simulation.

How does our estimate compare to other estimates of Operation Twist? Note that the policy we evaluate is not QE1 or QE3. The policy experiment is one in which the size of the central bank balance sheet remains the same. We find the model with anticipation corresponds particularly well to the Twist-announcement, which was part of QE2. Chen et al. (2012) and Gertler and Karadi (2013) evaluate the impact of the November 2010 announcement of QE2. Both our experiment and theirs leave the consolidated government's balance sheet unchanged. However, Operation Twist 1 has a particularly simple time series profile, which in addition to the anticipation horizon, corresponds particularly well with the estimated model.

Chen et al. (2012) find a similar impact of a maturity switch on long term interest rates (a reduction of 11 basis points), though the exact policy experiment they conduct is somewhat different from ours. Despite the similar effect on long term interest rate, they find a much smaller effect on real variables. This is a consequence of the fact that the degree of market segmentation in their model is relatively small. The real effects in the present model are larger primarily because fluctuations in maturity *are* found to be important in relation to the macro data.

Swanson (2011) argues that the original "Operation Twist" performed by the Fed in the sixties is very similar in size to that under QE2. He estimates the effect of that operation to have reduced long term interest rates by 15 basis points, which is rather similar to the estimated interest rate effect in our model.

Finally, let us dwell briefly on a few specifics underlying our evaluation, and how they accord with details of the actual policy implementation. First, the anticipation horizon in the model is four quarters, which largely coincides with the difference between the announcement date and the completion of the program as announced. Second, in the model the switch in maturity is implemented in $t+4$ entirely, while the Fed purchased and sold assets gradually, with a completion date four quarters later. Third, our evaluation pertains to "Operation Twist 1". In June 2012 the Fed announced an extension of the program until year end, "Operation Twist 2", which our evaluation does not take into account. If anything, we expect the real effects to be larger if we had. Finally, Operation Twist involved a switch in maturities which is not exactly conform with the maturity composition in the data used for estimation. Specifically, the data splits short and long bonds at a one year maturity, as in Chen et al. (2012). Operation Twist increased bond holdings of maturities six years and above, and reduced bond holdings with maturities of three years and less.

5.2 Anticipated interest rate shocks

Figure 6 shows the short term interest rate during the crisis, along with the estimated anticipated policy shocks (ε^{r}_{t-4}) to the interest rate equation. A positive anticipated shock at date t implies agents expect the interest rate one year later to be high relative to the policy rule. The estimation finds the start of the crisis to be characterized by a sequence of positive anticipated shocks. The model thus suggests that the zero lower bound was binding at that point. Interestingly, the shock turns negative in 2009 and almost invariably stays negative from then onward. The timing coincides with the introduction (and continuation) of the Fed's forward guidance. Taken at face value, this suggests Fed announcements since 2009 have signalled the policy rate will remain lower for longer than implied by its historical policy rule.

Anticipated policy shocks give rise to effects detailed in Figure 7. The quantitative response of all debt variables is tiny compared to their overall variance. Most of the action is present in the bottom half of the figure. Specifically, an anticipated reduction of the policy rate four quarters hence boosts output and inflation on impact. The expansion is due to a fall in the real rate. As detailed in De Graeve et al. (2014), nominal interest rates across the maturity spectrum need not fall on impact. The nominal short rate increases as a result of the policy rule leaning against the boom. The nominal long term interest rate increases as well, through a standard expectations channel.

5.3 The real effects of unconventional monetary policy

Summing up, Figure 8 shows the evolution of GDP during the crisis (thick solid line) and how policy has contributed to it. The dotted line shows the contribution of anticipated interest rate shocks to GDP. Early on in the crisis these shocks drag GDP down as agents believe the policy rate will remain above the level dictated by the policy rule, arguably due to the ZLB. In 2009:Q3 this effect bottoms out, the policy rate is expected to remain lower for longer until the end of the sample. This arguably captures the effect of Forward Guidance. Cumulatively, through to peak, this has increased GDP by 2%-points.

The dotted line shows how shifts in maturity of the consolidated government debt have contributed to GDP. This measures the combined impact of both the Fed and Treasury, whose policies were uncoordinated and may have offset one another (Greenwood et al., 2015a). The fact that the dotted line ends almost exactly at the level where it was pre-crisis suggests that maturity policy of the consolidated government has not provided much economic stimulus.

The dashed line gives a cleaner measure of one of the various policies conducted: it measures how maturity policy would have contributed to GDP had the Fed not announced Operation Twist 1. The output effect (the difference between the dotted and the dashed line) peaks at 0.6%-points. This effect on output is quantitatively significant in its own right. As such it is distinct from other DSGE studies that found smaller effects, such as Chen et al. (2012) or Gertler and Karadi (2013), especially when abstracting from the lower-for-longer effect embedded in their counterfactuals.

6 Extensions

6.1 Endogenous maturity supply

Decisions about the maturity composition of debt need not be exogenous. Maturity policy can and possibly should be determined depending on multiple objectives, as argued in Greenwood et al. (2015b). In light of that, we augment the maturity supply policy rule with reaction coefficients to the following variables: Short and long term interest rates are an obvious input into cost minimization considerations for the Treasury. To the extent that maturity policy is geared toward aggregate demand management, it may well respond to output and inflation (or growth, or the respective gaps). For each of these variables, we choose a prior that is centered around zero.

We have experimented with a number of different specifications that differ depending on whether the level of interest rates is included or only the spread, and on whether inflation and output are specified in deviation from their target or not. Across these specifications a few robust results stand out. In Table 2 we present the coefficient estimates of a maturity supply rule that allows for a response to the short and long term interest rate, to output (relative to the flex-price counterpart), and to inflation (in deviation from its target). Specifically, the estimates presented are for the maturity policy rule

$$\hat{b}_t^L - \hat{b}_t^S = m_{r^S}\hat{r}_t^S + m_{r^L}\hat{r}_t^L + m_y\widehat{y}_t + m_\pi\widehat{\pi}_t + \hat{\varepsilon}_{t-4}^{MAT} + \nu\hat{\varepsilon}_t^{TD}.$$

First, only few endogenous maturity-policy responses are found to be relevant. Specifically, higher output tends to be associated with increases in maturity. This is the only effect that is robustly different from the prior and precise across all specifications. From a cost minimisation perspective, one might expect maturity to lengthen when long term interest rates are low. The parameter estimate is not inconsistent with that, but is very imprecisely estimated. The response of the maturity composition to the short term policy rate does not seem to square with that logic. Overall, we hesitate inferring a more direct structural interpretation of these coefficients. Perhaps the unclear result is a consequence of the fact that maturity policy really is determined by different agents (both Fed and Treasury), each with their own objectives. Second, interpretation aside, the variance of exogenous maturity shocks is reduced. That said, they remain responsible for the bulk of fluctuations in maturity. Third, while most other parameters are unaffected, the maturity friction is estimated to be more important ($100\chi = 5.46$) compared to the benchmark model. Finally, allowing for endogenous maturity policy does not meaningfully change the estimated impact of QE, as is apparent from Figure 9.

6.2 Absolute effects

In the benchmark model the financial intermediary pays a (static or dynamic) adjustment cost whenever changing its portfolio composition relative to the preferred maturity composition $\delta = \frac{\bar{b}^L}{b^S}$. We here relax that adjustment cost function. Specifically, we now allow the adjustment cost to be separable in the quantity of long and short term bonds. In log-linear terms

$$\begin{aligned} \hat{r}_t^S - \hat{r}_t^h &= -\chi^L \left(\hat{\bar{b}}_t^L - \rho_{\chi^L} \hat{\bar{b}}_{t-1}^L \right) + \chi^S \left(\hat{b}_t^S - \rho_{\chi^S} \hat{b}_{t-1}^S \right) - \hat{\varepsilon}_t^b \\ E_t \hat{r}_{t+1}^L + E_t \hat{p}_{t+1}^L - \hat{p}_t^L - \hat{r}_t^h &= \frac{\chi^L}{\delta} \left(\hat{\bar{b}}_t^L - \rho_{\chi^L} \hat{\bar{b}}_{t-1}^L \right) - \frac{\chi^S}{\delta} \left(\hat{b}_t^S - \rho_{\chi^S} \hat{b}_{t-1}^S \right) - \hat{\varepsilon}_t^b. \end{aligned}$$

This specification enables policies like QE to have effects not just through the maturity composition of debt, but in principle also allows for the level of either long term or short term debt to have direct effects. We use the same priors as in the benchmark model and present parameter estimates in Table 2. We obtain very similar persistence parameters across maturities, but a fairly substantial difference in the estimated elasticities χ^L and χ^S.[12] The remaining model parameters are quite stable.

[12] The difference in elasticities is sensitive to variations in model specification, such as the inclusion of anticipation.

Thus, allowing for more flexibility in the form of adjustment costs hints at a slightly higher interest rate impact of long term bond quantities outstanding compared to short term bonds (in market value). That said, in terms of impulse responses this does not have large quantitative implications. Figure 9 shows the estimated effect of Operation Twist 1 in this model. If anything, QE becomes more powerful, as evident from a higher output peak.

7 Conclusion

The objective of this investigation is quantifying the effects of unconventional monetary policy. Our estimates suggest both quantitative easing and forward guidance have significantly contributed to staving off a further deepening of the crisis. To the extent that forward guidance can be captured by anticipated shocks to an interest rate rule, it has contributed to a cumulative 2%-point increase in GDP in the period 2009-2015. As a caveat to this particular result, our estimation does not explicitly incorporate a zero lower bound. That aside, our estimates lie within the range of those found in other estimated NK DSGE models. Rather differently from the extant DSGE literature, we do find substantial effects of Quantitative Easing. Specifically, “Operation Twist 1” is estimated to have increased GDP by 0.6%-points. Since this operation is only part of the total maturity switch implemented by the Fed under QE2, we view that estimate as a lower bound. Despite it being a lower bound, our estimate lies substantially above that found in alternative DSGE estimates. The main source of this higher estimated impact lies in a more comprehensive joint modeling of macro fluctuations, the term structure of interest rates and the maturity of government debt.

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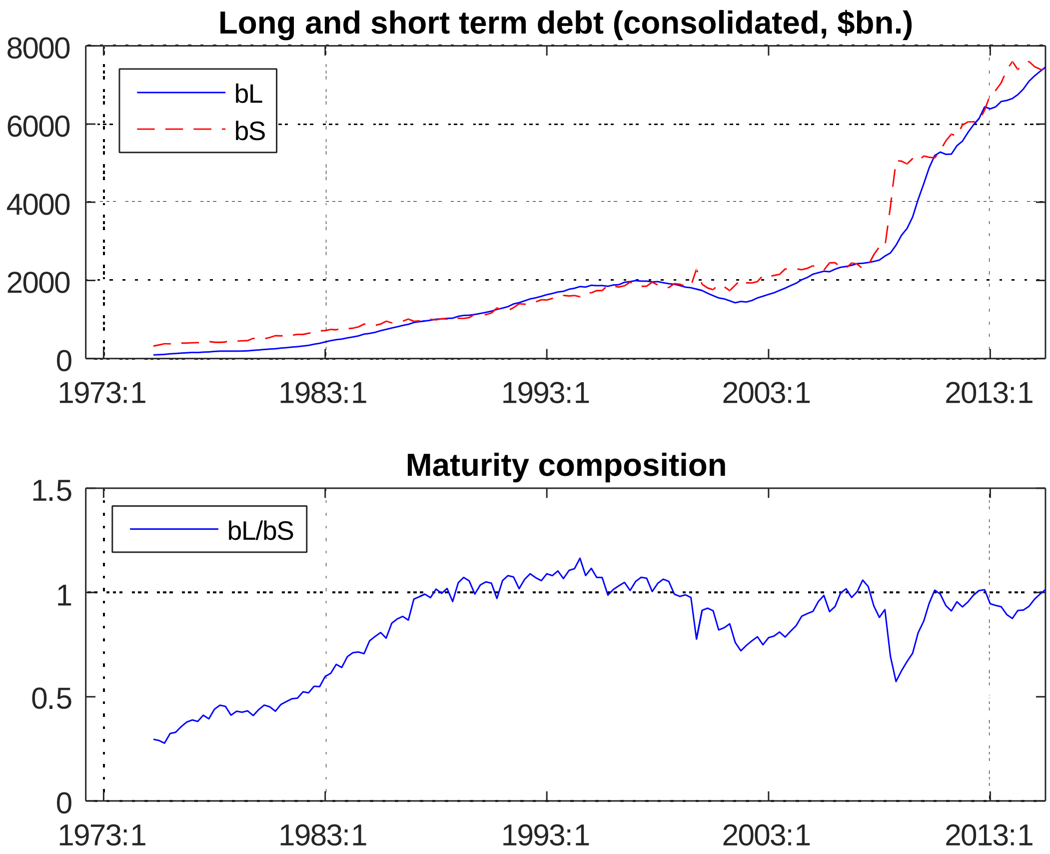
Table 1: Estimated parameters: Benchmark model

	Prior			Posterior	
	distr.	mean	s.d.	mode	s.d.
Financial block					
100χ	N	5	1	4.53	0.88
ρ_χ	B	.5	.2	0.98	0.01
δ	N	1	.05	1.06	0.05
Fiscal block					
ν	N	0	0.5	-0.42	0.06
c^b	N	2.3	0.3	2.49	0.10
θ	N	0.05	0.1	0.03	0.01
ϑ	G	0.5	0.25	0.22	0.01
Shocks					
σ^{MAT}	IG	1	2	4.11	0.23
σ^{TD}	IG	1	2	4.44	0.25
$\sigma^{\bar{\pi}}$	IG	.01	2	.05	.01
ρ_{TD}	B	0.5	0.2	0.51	0.07
$\rho_{\bar{\pi}}$	B	0.5	0.2	0.65	0.10

Note: Other model parameters and posterior simulation results in Appendix B.

Figure 1: Government debt composition: data



Note: Consolidated government debt in hands of the public, 1975:Q2-2015:Q3

Table 2: Estimated parameters: Models with anticipation

	Benchmark	Anticipation		Endog. pol.		Absolute	
Financial block							
100χ	4.53		5.16		5.46		-
ρ_χ	0.98		0.98		0.98		-
δ	1.06		1.07		1.06		1.07
Fiscal block							
ν	-0.42		-0.44		-0.44		-0.44
c^b	2.49		2.48		2.47		2.46
θ	0.03		0.04		0.04		0.04
ϑ	0.02		0.02		0.02		0.02
Shocks							
σ^{MAT}	4.11		-		-		-
σ^{TD}	4.44		4.41		4.41		4.41
$\sigma^{\bar{\pi}}$	0.05		0.06		0.06		0.06
ρ_{TD}	0.51		0.52		0.52		0.53
$\rho_{\bar{\pi}}$	0.65		0.57		0.59		0.58
Extra							
		σ^{MAT}_{-4}	3.96		3.81		3.96
		σ^{r}_{-4}	0.10		0.09		0.10
				m_{rS}	-0.47 (1.5)	χ^L	6.15
				m_{rL}	-1.02 (2.3)	χ^S	3.72
				m_y	1.6 (0.5)	ρ_{χ^L}	0.983
				m_π	1.8 (1.1)	ρ_{χ^S}	0.951
ML	-1703.22		-1698.98		-1699.42		-1703.90

Note: Posterior mode parameter estimates. St.d. in parenthesis.

Figure 2: Contributions to debt components

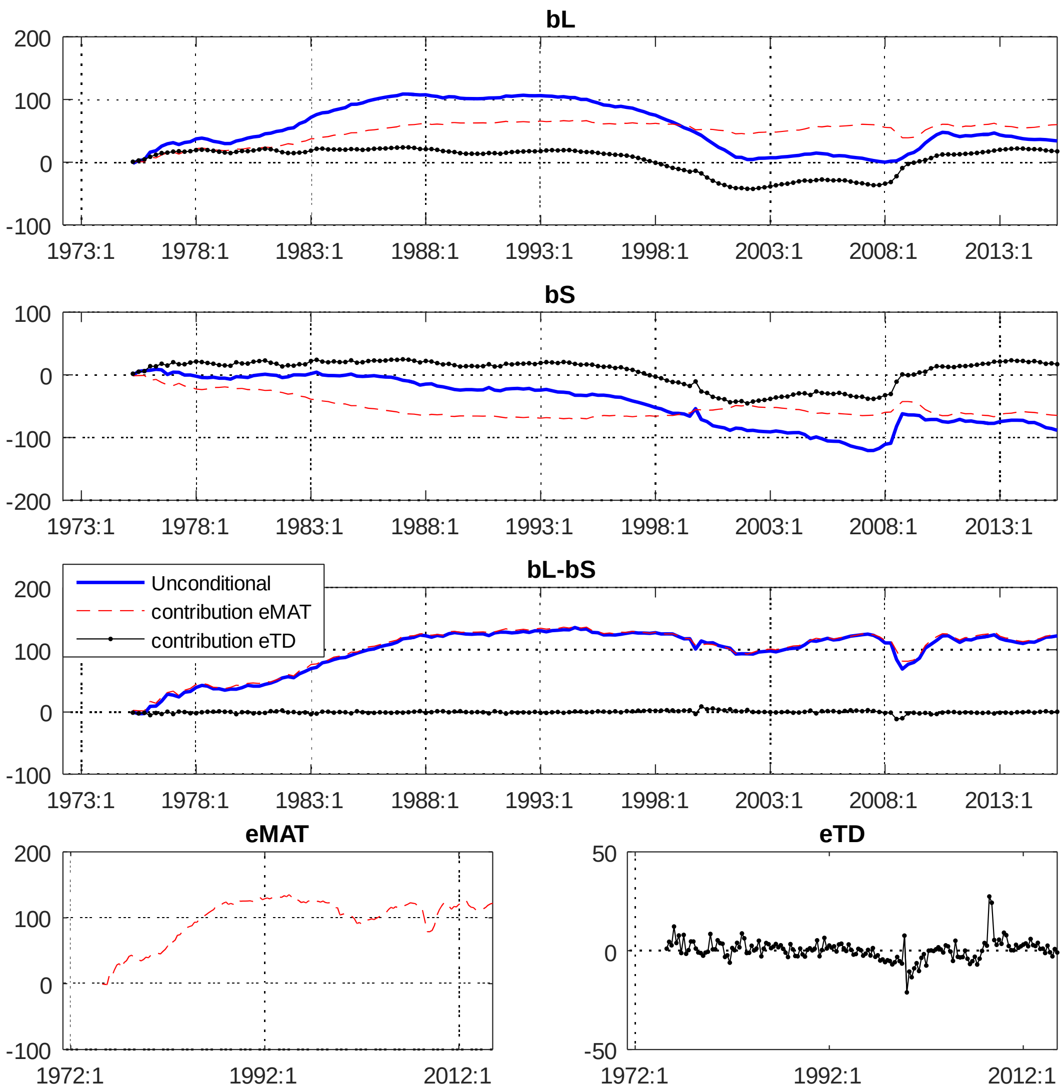
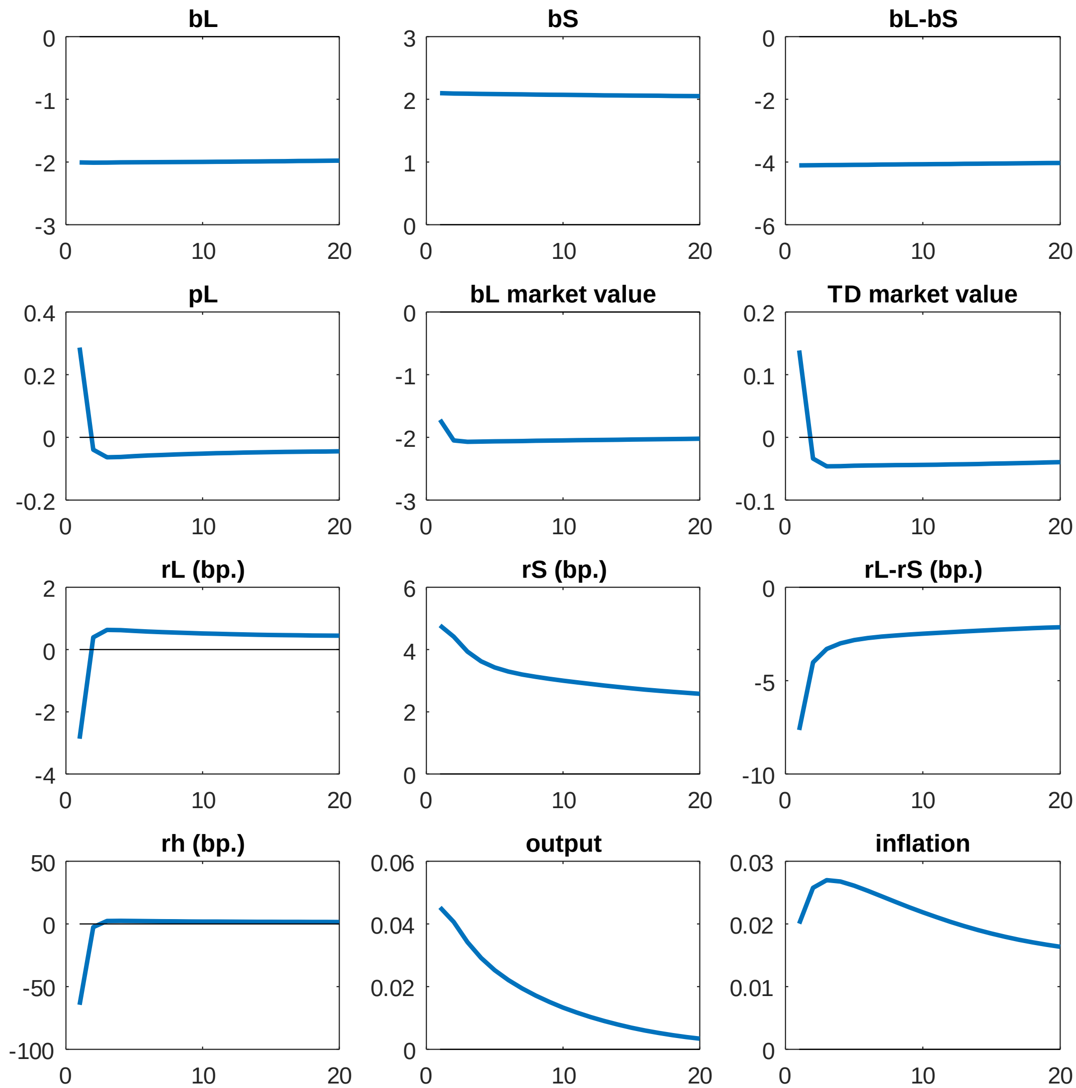


Figure 3: IRF: maturity shock



Note: Interest rates and inflation in annualized terms.

Figure 4: IRF: debt shock

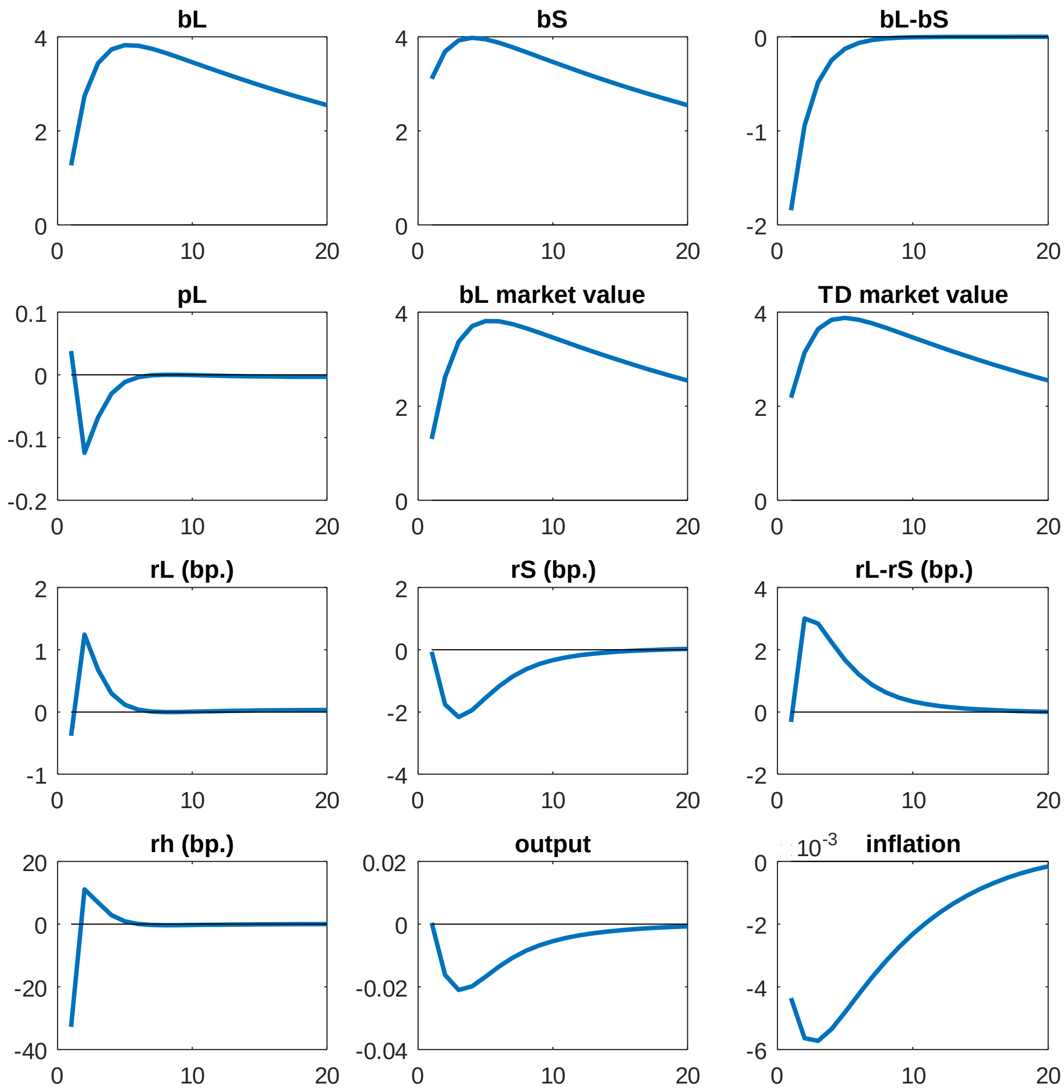


Figure 5: The effects of Operation Twist 1

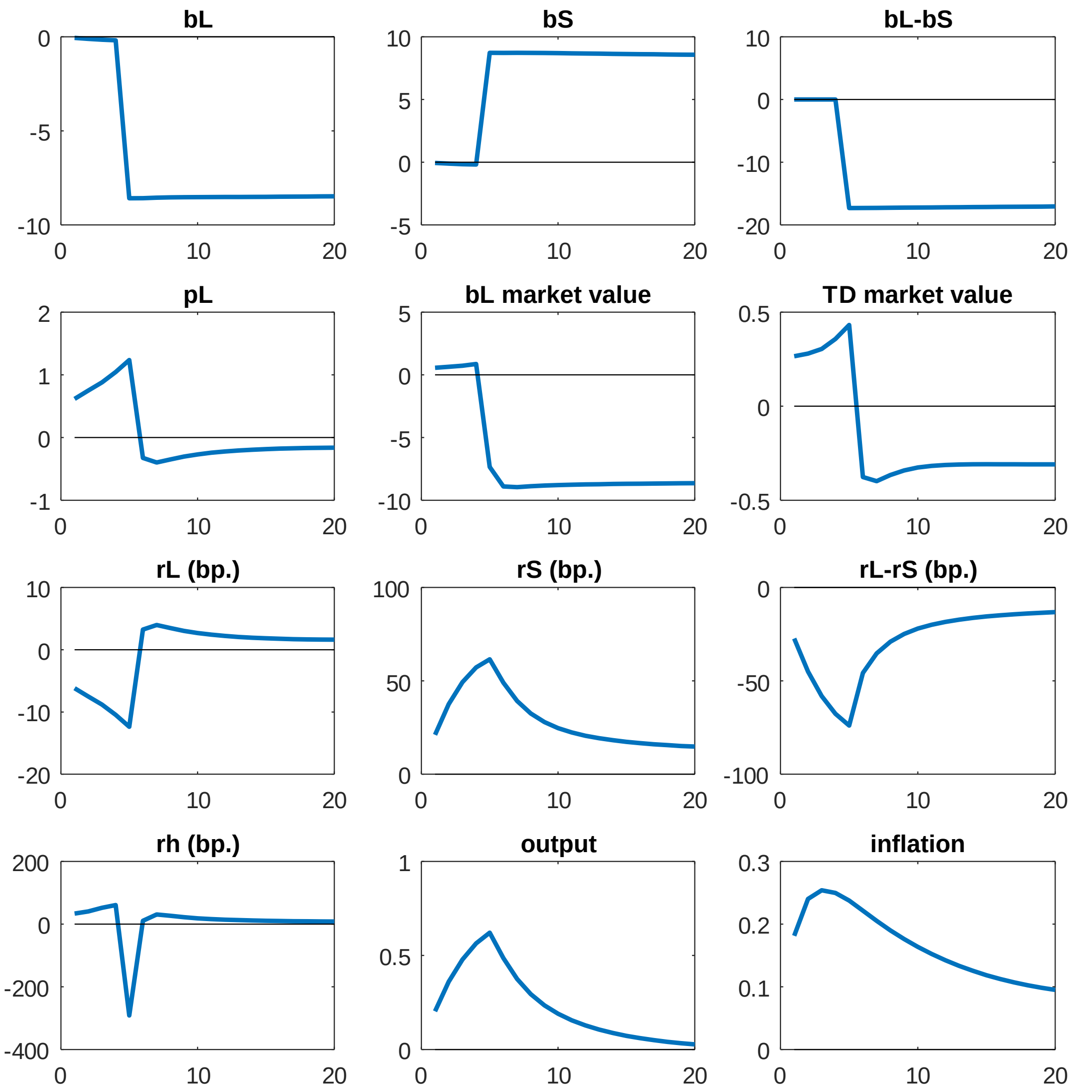


Figure 6: Anticipated interest rate shocks: 2007:Q1-2015:Q3

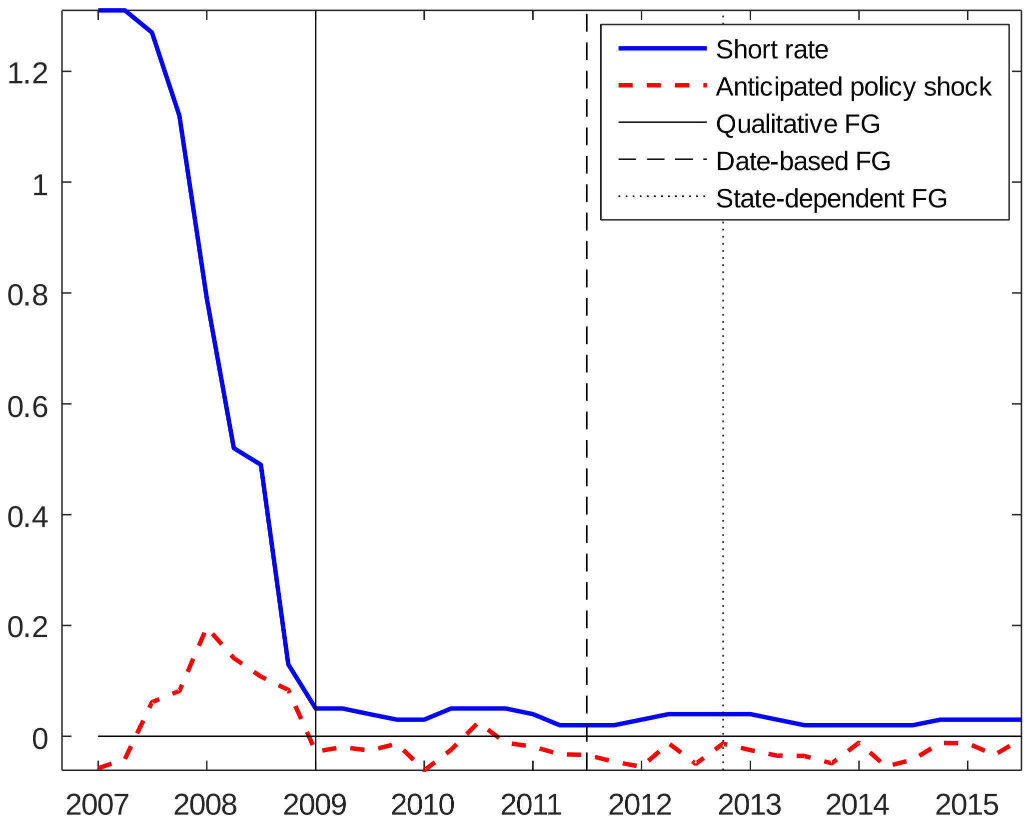


Figure 7: IRF: Anticipated interest rate shock

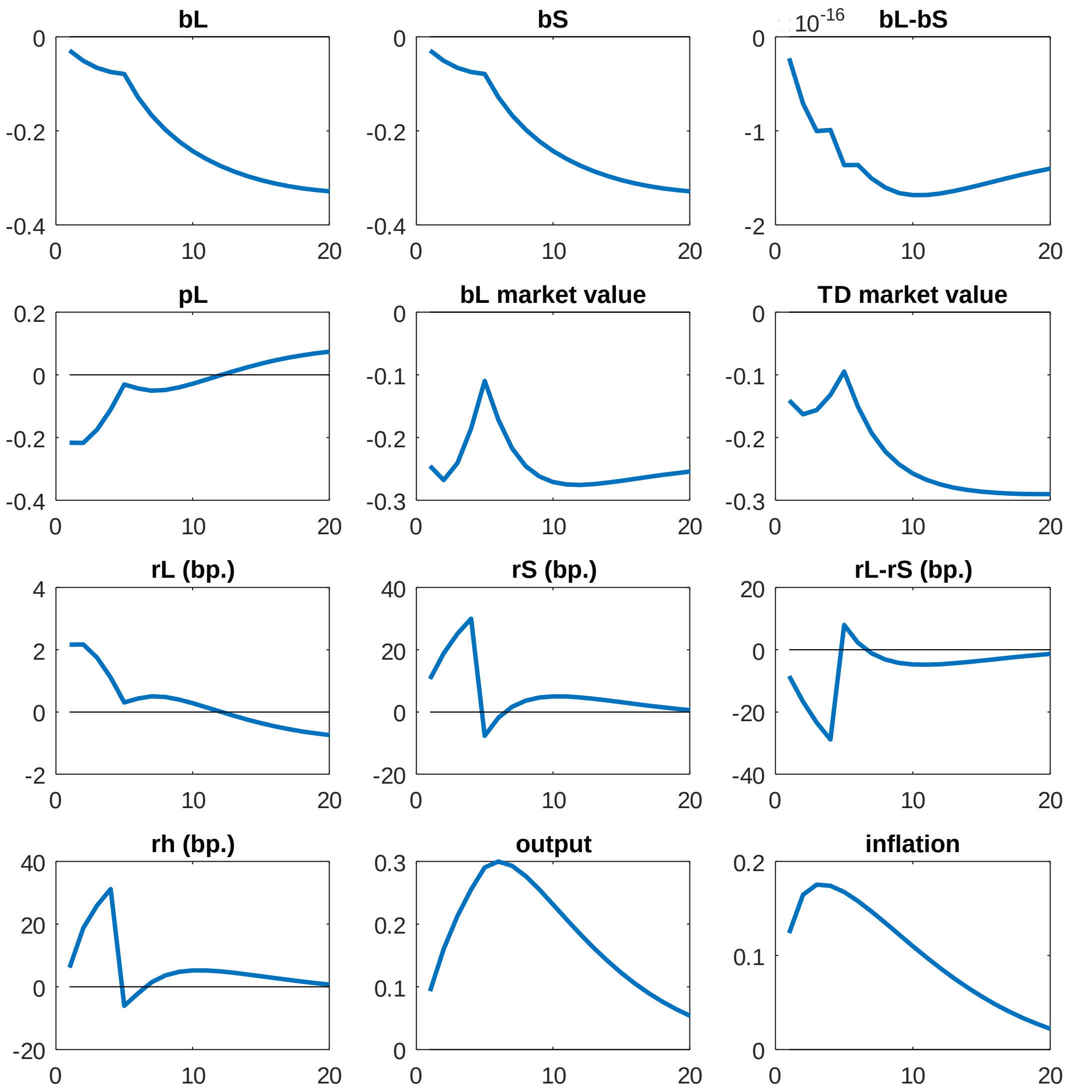


Figure 8: Unconventional policy contributions to GDP

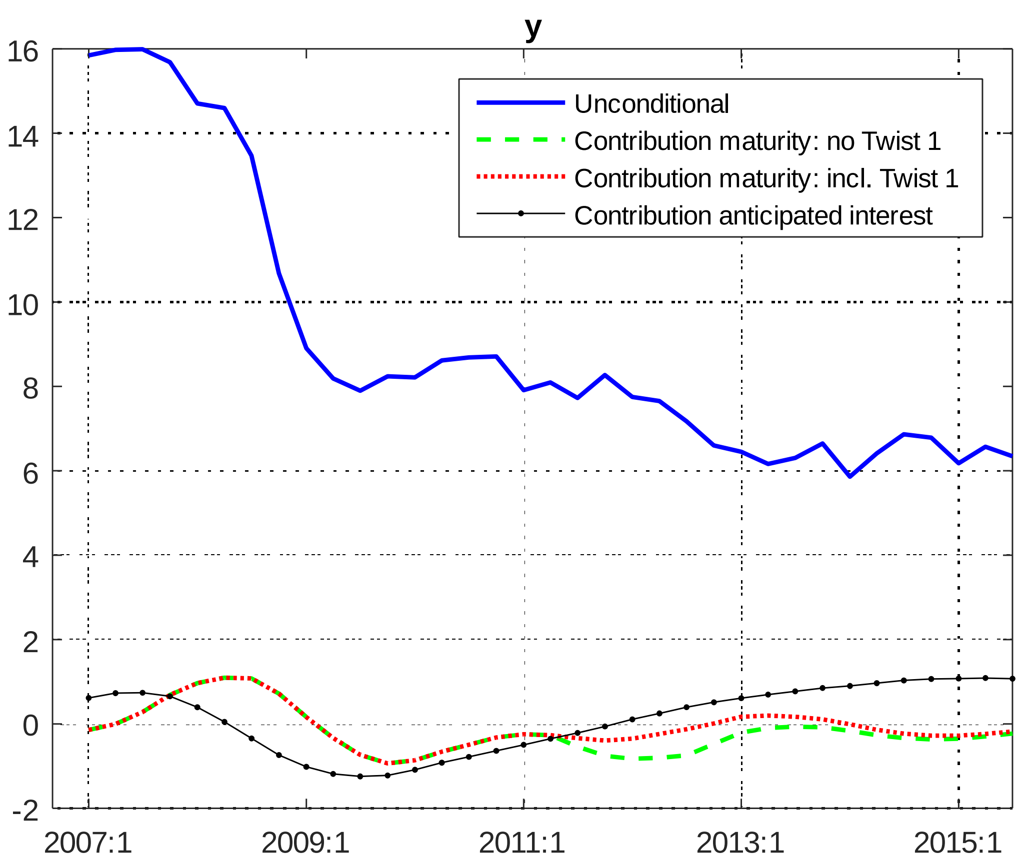


Figure 9: Operation Twist: Comparison across models