Alma Mater Studiorum – Università di Bologna

DOTTORATO DI RICERCA IN

ECONOMIA

Ciclo XXV

Settore Concorsuale di afferenza: 13/A1 – ECONOMIA POLITICA

Settore Scientifico disciplinare: SECS-P/01 – ECONOMIA POLITICA

Essays in Macroeconomics

Presentata da: Matteo Falagiarda

Coordinatore Dottorato | **Relatore**

Matteo Cervellati | Massimiliano Marzo

Esame finale anno 2014

Contents

Credit, Endogenous Collateral and Risky Assets: A DSGE Model

Matteo Falagiarda* Alessandro Saia†

December 2013‡

Abstract

This paper proposes a new Dynamic Stochastic General Equilibrium (DSGE) model with credit frictions and a banking sector, which endogenizes loan-to-value (LTV) ratios of households and banks by expressing them as a function of systemic and idiosyncratic proxies for risk. Moreover, the model features endogenous balance sheet choices and a novel formulation of the targeted leverage ratio, in which assets are risk-weighted by risk-sensitivity measures. The results highlighted in this paper are important along two dimensions. First of all, the presence of endogenous LTV ratios exacerbates the procyclicality of lending conditions. Second, the model contributes to deeper understand the role of prudential regulatory frameworks in affecting business cycle fluctuations and in restoring macroeconomic and financial stability. The results suggest that when the economy is severely stressed by shocks originating in the financial sector, prudential regimes such as *Basel II* and *Basel III* are capable of downsizing substantially aggregate volatility, with *Basel III* found to be significantly more effective than *Basel II*.

KEYWORDS: Banks, Leverage, DSGE models, Basel Accords
JEL Classification: E32, E44, E61

*Department of Economics, University of Bologna. Mail: matteo.falagiarda2@unibo.it Address: Piazza Scaravilli 2 - 40126 Bologna (Italy). Office Phone: +39 051 2092641

†Department of Economics, University of Bologna

‡We benefited from the encouragement and suggestions of Massimiliano Marzo and Paolo Zagaglia. We thank participants at the 5th Conference of the International Finance and Banking Society. The usual disclaimer applies.

1 Introduction

Until the early 2000s, large-scale structural macro models, such as Dynamic Stochastic General Equilibrium (DSGE) models, have often neglected financial and credit dynamics, with a few notable exceptions (Christiano et al., 2003). Most of the policy models currently employed by central banks (Smets and Wouters, 2003; Christiano et al., 2005; Christoffel et al., 2008) either assume frictionless financial markets or lack a realistic and comprehensive representation of the financial sector.

The recent growing interaction between the real economy and financial markets along with the emergence of several questions linked to financial stability, macro-prudential regulations and monetary policy, has provided a strong motivation to create fully articulated macroeconomic models describing the role of financial frictions and structures in a modern market economy. As the recent global downturn unfolded, the necessity of reforming standard macro models along these lines has become even more urgent.

However, the literature on macroeconomic modeling and that regarding financial and credit market imperfections have run for a long time on parallel paths without converging.[1] As for the latter, it has long been recognized that financial markets are highly imperfect (Jaffee and Russell, 1976; Stiglitz and Weiss, 1981). Asymmetric information between borrowers and lenders, costly state verification issues, and the eventuality of bankruptcies, defaults and contagions, are the main factors that may potentially disrupt the smooth working of financial and credit markets. It follows that agents are not able to perfectly smooth consumption in reaction to shocks, and business cycle fluctuations are likely to be amplified.

This *financial accelerator* effect, whereby shocks to the net worth of agents have procyclical effects on their borrowing capacity, amplifying, in such a way, business cycle fluctuations, has been first formalized by Bernanke and Gertler (1989), and subsequently incorporated into structural macroeconomic models by Bernanke et al. (1996, 1999) and Kiyotaki and Moore (1997). In the first case, the so-called costly state verification setting,

[1] The following literature review is far from being exhaustive. For a comprehensive survey, see Roger and Vlcek (2012).

the financial accelerator effect occurs because the premium on external financing, which depends on the net worth, is procyclical, implying that economic disturbances influence the borrowing capacity of agents. In Kiyotaki and Moore (1997), the amplification of business cycles' magnitude and persistence arises because of the dynamic interactions between borrowing limits and asset prices, generated by explicitly modeling collateral for loans.

Frictions relying on the costly state verification and default risk à la Bernanke et al. (1999) and limited enforceability and collateralized debt à la Kiyotaki and Moore (1997) have been recently employed to enrich standard DSGE models (Aoki et al., 2004; Gertler et al., 2007; Christensen and Dib, 2008; Iacoviello, 2005; Iacoviello and Neri, 2010; Lombardo and McAdam, 2012).[2]

Most of the earlier macroeconomics literature imposed financial frictions on non-financial borrowers, treating financial intermediaries as a veil. Modeling financial intermediaries entails the presence of a more or less structured bank's balance sheet, which establishes a link between banking activity and the macroeconomy. Some recent models with financial intermediaries emphasize the *demand side* of credit, i.e. a perfectly competitive banking sector accommodates any changes in the demand for credit coming from households and firms (Christiano et al., 2003, 2008, 2010).

Another strand of the literature captures *supply side* aspects of credit dynamics by introducing a more realistic representation of financial intermediaries. First of all, the work by Gerali et al. (2010) paved the way to a flourishing literature that models banks with a certain degree of market power (Dib, 2010; Andrés and Arce, 2012). In Gerali et al. (2010), banks, by operating in monopolistically competitive markets, impose interest rates on loans and deposits that are, respectively, policy rate markups and markdowns. This amplifies the effect of policy rate movements for borrowers, and attenuates those for lenders. Therefore, the transmission mechanisms of shocks are richer in comparison with standard models.

[2]Recent extensions to these settings try to introduce endogenous default (Forlati and Lambertini, 2011), and substantial non-linearities to generate "occasionally binding" collateral constraints (Mendoza, 2010).

A second important element is the presence of bank capital and, in particular, capital requirements for banking activity. Bank capital requirements are usually imposed to limit the moral hazard on the part of banks arising with deposit insurance. However, capital requirements are costly because they reduce the possibility for banks to create liquidity. Meh and Moran (2010) introduce bank capital to model moral hazard problems between borrowers and investors. In other contributions (den Heuvel, 2008; Angeloni and Faia, 2013; Zhang, 2009; Dib, 2010; Gerali et al., 2010; Agénor et al., 2012; Angelini et al., 2012), bank capital is motivated by regulatory requirements. In fact, recent events have strengthened the role of the so-called "prudential" policies, namely policies that, focusing on the interactions between financial institutions, markets and the business cycle, aim at mitigating the impact of financial fluctuations.[3] Usual instruments of macro-prudential policies are countercyclical capital and liquidity requirements, and loan-to-value (LTV) ratios. Modeling bank capital requirements allows economists: a) to analyze the macroeconomic impact of regulations (e.g. how regulatory instruments can attenuate the tendency of the economy to over-leverage during booms and deleverage during busts);[4] b) to better capture the effect of shocks originating in financial markets; c) to study how the transmission of shocks is altered depending on the strength of the financial sector, and, in particular, how macro-prudential and monetary policies can be coordinated and combined effectively.[5]

Within this research area, Angelini et al. (2012), by adapting the model by Gerali et al. (2010), analyze the strategic interaction between macro-prudential policies and monetary policy. They consider two types of interaction between monetary and regulatory authorities: cooperative and non-cooperative interaction. Their results suggest that when the economy is hit by supply shocks (i.e. in normal times), macro-prudential policies have limited effect on macroeconomic stability. By contrast, when the economy is hit by

[3]Prudential policies are, for example, provided for by the Basel Accords. For an extensive and updated review on prudential policies see Beau et al. (2012) and Galati and Moessner (2012).

[4]There is indeed strong empirical evidence that bank leverage is strongly procyclical (Adrian and Shin, 2010b).

[5]As stressed by Beau et al. (2012), the reason for the close link between macro-prudential and monetary policies is that they work through the same transmission channels, such as the bank lending and the balance sheet channels.

financial shocks (i.e. in extraordinary times), macro-prudential policies help to stabilize macroeconomic fluctuations, and cooperation with monetary policy plays an important role in strengthening this effect.

By embracing the *supply side* approach in modeling the banking sector, this paper proposes a new DSGE model able to analyze the interconnections between financial markets and the macroeconomy. In particular, we adopt some of the elements present at the frontiers of research, highlighted above, and add to them. First of all, in line with some existing contributions in the literature, the model exhibits financially constrained households à la Iacoviello (2005), whose capacity to borrow is tied to the value of their real estate holdings, and a rich banks' balance sheet representation including deposits, loans to households, government bonds, loans from the central bank, and bank's equity. Hence, balance sheet choices are totally endogenous and the model features procyclical leverage.

Second, this leverage procyclicality is strengthened by the presence of proxies for measured risk, which are expressed in a novel formulation. While most of the existing general equilibrium models assume constant LTV ratios, empirical evidence shows that this value varies substantially over time, also reflecting movements in risk perception in financial markets (Gruss and Sgherri, 2009; Campbell and Cocco, 2011).[6] Partially drawing on Angelini et al. (2012), our setting endogenizes LTV ratios by expressing them as a function of proxies for both systemic and idiosyncratic risk, both at the level of households and banks.[7] Moreover, we propose a novel formulation of the targeted leverage ratio, in which assets are risk-weighted by cyclical risk-sensitivity measures.[8] Inspired by the empirical evidence suggesting that procyclical leverage affects aggregate volatility and particularly the price of risk (Adrian and Shin, 2010b), the proxies for risk perception and the risk-sensitivity measures depend, *inter alia*, on the leverage conditions

[6]Furthermore, LTV ratios vary significantly also across countries, reflecting differences in legal and regulatory frameworks (Calza et al., 2007).

[7]Endogenous LTV ratios have also been proposed by Lambertini et al. (2011). In this model, the endogenous LTV is derived based on an agency problem between lenders and borrowers.

[8]A similar formulation is proposed by Agénor et al. (2012), who relate instead the risk-measures to the repayment probability.

of households and banks.

The new role for risk combined with endogenous balance sheet choices, allows us, among the other things, to better analyze how financial intermediaries affect the conduct of monetary policy, and, in particular, to isolate the *risk-taking channel* of monetary policy described by Adrian and Shin (2010a). According to this channel, monetary policy actions affect the risk-taking capacity of banks, leading to shifts in the supply of credit.

Third, banks are subjected to the standard tool used by regulatory authorities, i.e. capital requirements. The innovative formulation of the targeted leverage ratio includes two types of banking assets, namely loans to households and government bonds. As already stressed, the targeted leverage ratio presents an endogenous source of risk perception that differs among asset classes. Since both loans to households and government bonds are considered risky assets, the model is particularly suitable to investigate in a realistic way the effectiveness of different prudential regimes.

A fourth key peculiarity of the model is the presence of a structured connection between financial intermediaries and the monetary authority in order to better capture monetary policy transmission dynamics. We do this by introducing financially constrained banks besides financially constrained households. More specifically, the amount of loans that banks can receive from the central bank is subject to a collateralized borrowing constraint. Loans to households and government bonds are assumed to be employed as collateral by banks. These features aim at reproducing the lending facilities usually offered by monetary authorities to banks.

In light of the novelties introduced, our model represents a unique instrument for simulating, within a general equilibrium framework, credit crunch dynamics and analyzing the effect of prudential regulatory measures. The results highlighted in the paper are important along two dimensions. First, the model provides new insights on the interactions between the banking and credit sectors and the rest of the economy. Second, and more importantly, it contributes to deeper understand the role of supervisory authorities in affecting business cycle fluctuations and in restoring macroeconomic and financial stability.

More precisely, our findings suggest that the presence of endogenous LTV ratios exacerbates the severity of a simulated credit crunch, and, more generally, the procyclicality of lending conditions, in comparison with a baseline model without these features, and it is thus able to reproduce the salient facts of the recent financial crisis. Endogenous risk weights and LTV ratios are capable of affecting substantially lending quantities, due to the interaction between: a) movements in the LTV ratios, due to changes in labor market- and macroeconomic conditions; b) movements in the weighted leverage cost, due to the combination of changes in interest rates and housing prices, which affect the perception of risk associated with mortgage assets held by banks.

Lastly, by modifying the configuration of the key parameters and steady-states of the model, we are able to compare different prudential policy regimes, such as the Basel Accords. The results suggest that when the economy is mainly affected by standard macroeconomic shocks (normal times), prudential regulatory regimes like *Basel II* and *Basel III* increase the volatility of macroeconomic and credit variables. By contrast, when the economy is severely stressed by shocks originating in the financial sector (extraordinary times), these regimes are capable of downsizing substantially aggregate volatility, making business cycle fluctuations smoother, with *Basel III* found to be significantly more effective than *Basel II*.

The remainder of the paper is organized as follows. Section 2 elaborates the model and introduces its key features. Section 3 presents the main results. Section 4 concludes.

2 The Model

A stylized representation of the model economy is sketched in Figure 1. The economy is populated by two types of households, namely constrained and unconstrained households. Constrained households supply labor inputs and accumulate housing stock, while unconstrained households supply capital inputs. Monopolistically competitive firms hire labor and capital to produce differentiated goods. The two groups of households exhibit a different discount factor, i.e. they discount differently the stream of future utility, which ensures positive financial flows in equilibrium. Thus, constrained households borrow a positive amount of loans from banks, whereas unconstrained households invest their resources by purchasing positive amounts of deposits and zero-coupon government bonds. The availability of loans to constrained households is subject to a borrowing constraint linked to the market value of their housing stock. Banks operate in a perfect competitive market. The asset side of their balance sheet is composed of government bonds and loans to households. They are assumed to purchase government bonds. Loans to households and purchases of government bonds are financed by collection of deposits, net worth, and loans from the central bank collateralized against banks' asset holdings.[9] Lastly, a consolidated government-central bank conducts: a) a standard passive fiscal policy; b) a standard monetary policy consisting in setting the policy rate via a Taylor rule; c) a monetary policy involving the lending facility for banks.

2.1 Constrained Households

Preferences of the representative constrained household are defined over consumption C_t^C, real money balances $\frac{M_t^C}{P_t}$, hours worked F_t, and real stock of housing $\frac{H_t}{P_t}$, and are described by the infinite stream of utility:

$$U_t^C = \sum_{t=0}^{\infty} \beta_C^t u^C \left(C_t^C, \frac{M_t^C}{P_t}, F_t, \frac{H_t}{P_t} \right) \tag{1}$$

where β_C is the intertemporal discount factor.
The instantaneous utility function of the representative constrained household $u^C \left(C_t^C, \frac{M_t^C}{P_t}, F_t, \frac{H_t}{P_t} \right)$ is given by:

$$u^C \left(C_t^C, \frac{M_t^C}{P_t}, F_t, \frac{H_t}{P_t} \right) = \frac{(C_t^C - \gamma C_{t-1}^C)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} + \frac{1}{1-\chi} \left(\frac{M_t^C}{P_t} \right)^{1-\chi} - \frac{\Psi}{1+1/\psi} F_t^{1+1/\psi} + J^h \log \frac{H_t}{P_t} \tag{2}$$

where γ measures the importance of consumption habits, σ is the elasticity of intertemporal substitution, χ is the elasticity of money demand, and ψ is the Frisch elasticity of

[9] This is a sort of discount window offered by the monetary authority to banks.

labor supply.

In this economy, each agent (both constrained and unconstrained) can choose the composition of a basket of differentiated final goods. Preferences across varieties of goods have the standard constant elasticity of substitution (CES) form à la Dixit and Stiglitz (1977):

$$C_t = \left[\int_0^1 C_t(j)^{\frac{\theta_t - 1}{\theta_t}} dj \right]^{\frac{\theta_t}{\theta_t - 1}} \tag{3}$$

where C_t is the aggregate consumption index of all the differentiated final goods produced in the economy under monopolistic competition. There are j-th varieties of final goods ($j \in [0, 1]$), and θ is the elasticity of substitution between different final goods varieties ($\theta > 1$).

Each constrained agent is subject to the following budget constraint:

$$C_t^C + \frac{P_t^H H_t}{P_t} + \frac{L_{t-1}^C R_{t-1}^C}{P_t} + \frac{M_t^C}{P_t} + T_t^C = \frac{M_{t-1}^C}{P_t} + \frac{L_t^C}{P_t} + w_t F_t + \frac{P_{t-1}^H H_{t-1}}{P_t} \tag{4}$$

Constrained agents allocate their wealth among money holding M_t^C and housing H_t, where P_t^H is the price of houses. They receive wage income $w_t F_t$, where w_t is the real wage (hereafter, lower-case letters denote real variables). They also pay a real lump-sum tax T_t^C. Constrained households borrow from banks an amount of loans L_t^C at the interest rate R_t^C. P_t is the aggregate price level. The housing stock is assumed to be fixed. A shock to the house price level, ν_t^H, is introduced. It follows an AR(1) process with an i.i.d. disturbance ε_t^{PH} with zero mean and standard deviation σ_{PH}.

Moreover, each constrained household is also subject to the following borrowing constraint:

$$\frac{L_t^C R_t^C}{P_t} \leq LTV_t^C E_t \left[\frac{P_{t+1}^H H_t}{P_{t+1}} \right] \tag{5}$$

Thus, constrained households can borrow from banks, but the expected value of their housing stock must guarantee repayment of loans and interests, as in Iacoviello (2005) and

Iacoviello and Neri (2010). LTV_t^C is the loan-to-value ratio of the constrained agent and reflects the preferences of banks. As stressed by Gerali et al. (2010), from a microeconomic point of view it can be interpreted as the cost of collateral repossession for banks in case of default. Differently from most of previous studies, which assume an exogenous LTV ratio, LTV_t^C is determined endogenously by the following equation:

$$\frac{LTV_t^C}{LTV^C} = \left(\frac{LTV_{t-1}^C}{LTV^C}\right)^{\phi_{LTV^C}} \left(\frac{P_t^H H_t}{P^H H}\right)^{\varphi_{1,H}} \left(\frac{w_t F_t}{wF}\right)^{\varphi_{2,H}} \left(\frac{Y_t}{Y}\right)^{\varphi_{3,H}} \exp\left(\varepsilon_t^{LTV^C}\right) \tag{6}$$

where variables without the temporal subscript denote steady-state values. ϕ_{LTV^C} is an autoregressive parameter, $0 < \phi_{LTV^C} < 1$, to model sluggish LTV changes over time. $\varepsilon_t^{LTV^C}$ is an i.i.d. shock with zero mean and standard deviation σ_{LTV^C}. In the right-hand side of (6) we can distinguish other three terms. The first term represents the variation in the value of the stock of houses held by constrained households relative to its steady-state value, and it is a proxy for the value of the collateral. The second term measures variations in the labor income of constrained households relative to its steady-state value to capture the risk related to households' income fluctuations. We then add a component associated with fluctuations of output around its steady-state level: it is a proxy for the systemic risk of the economy. It is assumed that $\varphi_{1,H}$,$\varphi_{2,H}$,$\varphi_{3,H} \geq 0$, i.e. increases in the value of the stock of houses, real labor income, and aggregate income, lead to an increase in the LTV ratio, allowing constrained households to expand their borrowing capacity. Thanks to this formulation, we are able to endogenize the amount of credit that banks provide to constrained households given the value of their collateral.

Constrained households maximize their lifetime utility (1), subject to the budget constraint (4) and the borrowing constraint (5). The first order necessary conditions with respect to consumption, labor, money, houses, and loans are respectively given by:

$$\left(C_t^C - \gamma C_{t-1}^C\right)^{-1/\sigma} - \beta_C \gamma E_t\left[\left(C_{t+1}^C - \gamma C_t^C\right)^{-1/\sigma}\right] = \lambda_t^C \tag{7}$$

$$\Psi F_t^{1/\psi} = \lambda_t^C w_t - E_t \left[\frac{\mu_t^C \varphi_{2,H} LTV_t^C P_{t+1}^H}{\pi_{t+1}} \right] \tag{8}$$

$$\left(m_t^C\right)^{-\chi} + \beta_C E_t \left[\frac{\lambda_{t+1}^C}{\pi_{t+1}} \right] = \lambda_t^C \tag{9}$$

$$\frac{J^h}{h_t} = \lambda_t^C P_t^H - E_t \left[\frac{\beta_C \lambda_{t+1}^C P_t^H}{\pi_{t+1}} \right] - E_t \left[\frac{\mu_t^C LTV_t^C P_{t+1}^H}{\pi_{t+1}} \right] - E_t \left[\frac{\mu_t^C \varphi_{1,H} LTV_t^C P_{t+1}^H}{\pi_{t+1}} \right] \tag{10}$$

$$\lambda_t^C = \beta_C E_t \left[\frac{\lambda_{t+1}^C R_t^C}{\pi_{t+1}} \right] + \mu_t^C R_t^C \tag{11}$$

where λ_t^C and μ_t^C are the Lagrange multipliers, and π_t is the gross inflation rate ($\pi_t = P_t/P_{t-1}$).

2.2 Unconstrained Households

The preferences of the representative unconstrained households are defined over consumption C_t^U and an aggregator of real monetary assets x_t, and are described by the infinite stream of utility:

$$U_t^U = \sum_{t=0}^{\infty} \beta_U^t u^U \left(C_t^U, x_t\right) \tag{12}$$

where β_U is the intertemporal discount factor. In line with the existing literature, we assume that $\beta_U < \beta_C$, so that agents with a lower discount factor are savers in equilibrium, whereas agents with a higher discount factor are borrowers in equilibrium.

The instantaneous utility function of the representative unconstrained household $u^U \left(C_t^U, x_t\right)$

is given by:

$$u^U\left(C_t^U, x_t\right) = \frac{(C_t^U - \gamma C_{t-1}^U)^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} + \eta_x \log x_t \tag{13}$$

where $\eta_x > 0$. Drawing on Agénor et al. (2012), the composite index of real monetary assets x_t is defined via a Cobb-Douglas function:

$$x_t = \left(m_t^U\right)^v d_t^{1-v} \tag{14}$$

where m_t^U indicates real money balances, d_t real deposits. v measures the importance of real money balances in the liquidity bundle $(0 < v < 1)$.[10]

Each unconstrained agent is subject to the following budget constraint:

$$\frac{B_t^U}{P_t R_t^B} + \frac{M_t^U}{P_t} + C_t^U + T_t^U + \frac{D_t}{P_t} + I_t(1 + AC_t^I) = \frac{B_{t-1}^U}{P_t} + \frac{M_{t-1}^U}{P_t} + \frac{D_{t-1}R_{t-1}^D}{P_t} + q_t K_t + (1-\phi^B)\Omega_t^B \tag{15}$$

Thus, unconstrained agents allocate their wealth among money holding M_t^U, deposits D_t, which pay an interest R_t^D, and holding of zero-coupon government bonds B_t^U. They receive rental income $q_t K_t$ (where K_t is capital and q_t the rental rate), and a fraction $(1-\phi^B)$ of banks' profits Ω_t^B. They also pay a real lump-sum tax T_t^U. I_t is investment.

Unconstrained households accumulate capital and rent it to firms. The law of motion of capital stock is expressed in the following standard way:

$$K_t = I_{t-1} + (1-\delta)K_{t-1} \tag{16}$$

where δ represents the depreciation rate of the capital stock. In addition, unconstrained

[10] This formulation originates from a recent approach of modeling transaction services via CES bundles of different assets. See, for example, Canzoneri et al. (2008, 2011).

households face quadratic adjustment costs of investment as in Kim (2000):

$$AC_t^I = \frac{\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2 \tag{17}$$

where ϕ_K is the adjustment cost scale parameter for capital.

Unconstrained households maximize their lifetime utility (12), subject to the budget constraint (15) and the capital accumulation equation (16). The first order necessary conditions with respect to consumption, money, deposits, bonds, capital and investment are respectively given by:

$$(C_t^U - \gamma C_{t-1}^U)^{-1/\sigma} - \beta_U \gamma E_t\left[(C_{t+1}^U - \gamma C_t^U)^{-1/\sigma}\right] = \lambda_t^U \tag{18}$$

$$\frac{\eta_x \upsilon}{m_t^U} + \beta_U E_t\left[\frac{\lambda_{t+1}^U}{\pi_{t+1}}\right] = \lambda_t^U \tag{19}$$

$$\frac{\eta_x(1-\upsilon)}{d_t} + \beta_U E_t\left[\frac{\lambda_{t+1}^U R_t^D}{\pi_{t+1}}\right] = \lambda_t^U \tag{20}$$

$$\beta_U E_t\left[\frac{\lambda_{t+1}^U}{\pi_{t+1}}\right] = \frac{\lambda_t^U}{R_t^B} \tag{21}$$

$$\beta_U(1-\delta)E_t\left[\mu_{t+1}^U\right] = \mu_t^U - \lambda_t^U\left(q_t + \phi_K\left(\frac{I_t}{K_t}\right)^3\right) \tag{22}$$

$$\beta_U E_t\left[\mu_{t+1}^U\right] = \lambda_t^U\left(1 + \frac{3}{2}\phi_K\left(\frac{I_t}{K_t}\right)^2\right) \tag{23}$$

where λ_t^U and μ_t^U are the Lagrange multipliers.

2.3 Firms

The firms' sector is modeled in a standard way. Each j-th firm produces and sells differentiated final goods in a monopolistically competitive market. The production function is a standard Cobb-Douglas with labor provided by constrained households and capital by unconstrained households (i.e. the owners of firms):

$$Y_t = A_t K_t^{\alpha} F_t^{1-\alpha} - \Phi \tag{24}$$

where α is the share of capital used in production, and Φ is a fixed cost to ensure that profits are zero in the steady-state. A_t is technology and follows an AR(1) process:

$$\log\left(\frac{A_t}{A}\right) = \phi_A \log\left(\frac{A_{t-1}}{A}\right) + \varepsilon_t^A \tag{25}$$

where ε_t^A is an i.i.d. shock with zero mean and standard deviation σ_A.

Firms' optimizing process is constrained by nominal rigidities à la Rotemberg (1982), i.e. firms face quadratic price adjustment costs:

$$AC_t^P = \frac{\phi_P}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \pi\right)^2 Y_t \tag{26}$$

Given the standard CES setting of equation (3), the demand function faced by each single firm j is:

$$Y_t(j) = \left[\frac{p_t(j)}{P_t}\right]^{-\theta_t} Y_t \Longrightarrow P_t(j) = \left[\frac{Y_t(j)}{Y_t}\right]^{-\frac{1}{\theta_t}} P_t \tag{27}$$

Thus, the demand function for each single good j is proportionally related to the output level of the economy, and negatively to the price of good j.

Following Kim (2000), the profit function for each firm j is:

$$P_t\Pi_t(j) = P_t(j)Y_t(j) - P_t w_t F_t(j) - P_t q_t K_t(j) - P_t AC_t^P \tag{28}$$

After employing (26) and (27) into (28), the maximization problem of each firm becomes fully dynamic: each firm maximizes the expectation of the discounted sum of profit flows, given the information at time 0:

$$\Pi_0(j) = E_0\left[\sum_{t=0}^{\infty} \rho_t P_t \Pi_t(j)\right] \tag{29}$$

where ρ is the discount factor of firms.

By assuming that each agent in the economy has access to a complete market for contingent claims, the discount factors of unconstrained households and firms are equal:

$$E_t\left[\frac{\rho_{t+1}}{\rho_t}\right] = \beta^U E_t\left[\frac{\lambda_{t+1}^U}{\lambda_t^U}\right] \tag{30}$$

Therefore, the necessary first order conditions of the maximization problem with respect to labor and capital are given respectively by:

$$w_t = (1-\alpha)\left(\frac{Y_t + \Phi}{F_t}\right)\left(1 - \frac{1}{e_t^Y}\right) \tag{31}$$

$$q_t = \alpha\left(\frac{Y_t + \Phi}{K_t}\right)\left(1 - \frac{1}{e_t^Y}\right) \tag{32}$$

where e_t^Y is the output demand elasticity:

$$\frac{1}{e_t^Y} = \frac{1}{\theta}\left\{1 - \phi_P(\pi_t - \pi)\pi_t + \beta^U \phi_P E_t\left[\frac{\lambda_{t+1}^U}{\lambda_t^U}(\pi_{t+1} - \pi)\pi_{t+1}^2 \frac{Y_{t+1}}{Y_t}\right]\right\} \tag{33}$$

which measures the gross price markup over marginal cost. It is easy to check that manipulations of the log-linearized version of (33) lead to the standard New Keynesian

Phillips curve.

2.4 Banks

The banking sector is characterized by a continuum of banks facing perfect competition.[11] Banks borrow from the central bank L_t^{CB} at the rate R_t^{CB} (i.e. the policy rate) and receive deposits D_t from unconstrained households (liability side of the balance sheet), invest in government bonds B_t^B and provide loans to constrained households L_t^C (asset side of the balance sheet). Thus, the balance sheet identity of the representative bank is given by:

$$B_t^B + L_t^C = Z_t + D_t + L_t^{CB} \tag{34}$$

where Z_t represents the equity (net worth, capital) of the bank.

Each bank maximizes the present discounted value of its profits:

$$\begin{aligned} &E_0 \sum_{t=0}^{\infty} \beta_B [\frac{R_t^C L_t^C}{P_t} - \frac{L_{t+1}^C}{P_t} + \frac{R_t^B B_t^B}{P_t} - \frac{B_{t+1}^B}{P_t} - \frac{R_t^D D_t}{P_t} + \frac{D_{t+1}}{P_t} - \frac{Z_t}{P_t} + \frac{Z_{t+1}}{P_t} - \\ &- \frac{R_t^{CB} L_t^{CB}}{P_t} + \frac{L_{t+1}^{CB}}{P_t} - \frac{e}{2} \left(\frac{w_t^C L_t^C + w_t^G B_t^B}{Z_t} - \nu^b \right)^2 \frac{Z_t}{P_t} - \frac{\gamma^C}{2} \left(\frac{L_t^C}{P_t} \right)^2] \end{aligned} \tag{35}$$

where β_B is the discount factor of banks. The second to last term in (35) represents a quadratic cost that banks pay in terms of their equity whenever they move away from a leverage ratio ν^b (i.e. assets over equity) imposed by regulators. The presence of these costs is justified by the recent experience of many advanced economies, where authorities have proposed to introduce a leverage ratio as a regulatory tool. By modifying the imposed leverage ratio, it is possible to assess the impact of a stricter or looser macro-prudential policy.[12] The presence of capital requirements combined with a balance sheet identity like (34) has important implications for the dynamics of the model. In fact, any economic disturbance that affects banks' balance sheet composition forces financial

[11] An extension with monopolistic competition à la Gerali et al. (2010) is left for future research.

[12] For simplicity, we do not distinguish between required capital and countercyclical capital buffers held voluntarily by banks. For a discussion, see Angelini et al. (2010). Moreover, we do not introduce a countercyclical capital requirements rule as in Angelini et al. (2011).

intermediaries to modify their leverage, leading to shifts in the supply of credit. As highlighted by Adrian and Shin (2010a), this transmission channel played a crucial role in the recent crisis. The last term in equation (35) captures an additional cost of managing loans to households.

Drawing on Roger and Vlček (2011), the leverage ratio incorporates two different risk weights for loans to households (w_t^C) and government bonds (w_t^G). These variables can be considered proxies for the perception of the risk embedded in the asset side of the balance sheet of banks. The time-varying risk weights aim at capturing the nature of risk-sensitive regulatory frameworks such as *Basel II* and *Basel III*. We propose the following novel formulation for the two risk weights:

$$\frac{w_t^G}{w^G} = \left(\frac{w_{t-1}^G}{w^C}\right)^{\phi_{w^G}} \left(\frac{B_t}{Y_t}\kappa_B\right)^{\varphi_{1,w^G}} \left(\frac{Y_t}{Y}\right)^{\varphi_{2,w^G}} \exp\left(\varepsilon_t^{w^G}\right) \tag{36}$$

$$\frac{w_t^C}{w^C} = \left(\frac{w_{t-1}^C}{w^C}\right)^{\phi_{w^C}} \left(\frac{L_t^C R_t^C}{P_t^H H_t}\kappa_L\right)^{\varphi_{1,w^C}} \left(\frac{L_t^C}{Z_t}\kappa_Z\right)^{\varphi_{2,w^C}} \left(\frac{Y_t}{Y}\right)^{\varphi_{3,w^C}} \exp\left(\varepsilon_t^{w^C}\right) \tag{37}$$

where $\varphi_{1,w^G}, \varphi_{1,w^C}, \varphi_{2,w^C} \geq 0$, $\varphi_{2,w^G}, \varphi_{3,w^C} \leq 0$, and $\kappa_B = \frac{Y}{B}$, $\kappa_L = \frac{P^H H}{L^C R^C}$, and $\kappa_Z = \frac{Z}{L^C}$. ϕ_{w^G} and ϕ_{w^C} are autoregressive parameter ($0 < (\phi_{w^G}, \phi_{w^C}) < 1$). $\varepsilon_t^{w^G}$ and $\varepsilon_t^{w^C}$ are i.i.d. shocks with zero mean and standard deviation σ_{w^G} and σ_{w^C}, respectively.

The intuition behind (36) and (37) is as follows. Equation (36) models the risk associated with government debt. This risk is assumed to increase with government's total debt exposure (B_t/Y_t). The first term in the right-hand side of (37) represents a proxy for the leverage position of constrained households, expressed as the ratio between the value of loans and the value of household's collateral: the higher is this ratio, the higher is the perceived risk associated with L_t^C. The second term indicates the risk embedded in the balance sheet of banks: the perceived risk is an increasing function of the ratio between the amount of loans provided to households and the equity of banks. Thus, the sign of φ_{1,w^C} and φ_{2,w^C} in our calibration suggests that the risk increases as the leverage of households and the exposure of banks increase. Lastly, both equations feature a component related to the macroeconomic situation capturing systemic risk. Notice that if w_t^G and w_t^C are assumed to be fixed and equal to 1 (as in the steady-state situation), the leverage cost in equation (35) boils down to the more standard formulation usually adopted in the literature.

Equation (35) highlights another source of financing for banks (besides deposits from unconstrained households), namely loans from the central bank. Since this reflects standard lending facilities usually provided for by monetary authorities, banks are required to offer collateral. Therefore, similarly to what seen for constrained households, each bank is subject to a borrowing constraint:

$$\frac{R_t^{CB} L_t^{CB}}{P_t} \leq \phi_B^{CB} LTV_{B,t}^{CB} E_t \left[\frac{B_t^B}{R_{t+1}^B P_{t+1}} \right] + \phi_C^{CB} LTV_{C,t}^{CB} E_t \left[\frac{L_t^C}{R_{t+1}^C P_{t+1}} \right] \tag{38}$$

Thus, equation (38) introduces a collateralized lending market between banks and the central bank. Both government bonds (the first term on the right-hand side) and mortgage-backed securities (the second term on the right-hand side) can be considered as general collateral. The parameters ϕ_B^{CB} and ϕ_C^{CB} indicate the importance of each component ($\phi_B^{CB} + \phi_C^{CB} = 1$). Notice that usual standard lending facilities do not allow banks to use asset-backed securities as eligible collateral. Therefore, in the baseline calibration, the parameter ϕ_C^{CB} has been set to a low level (0.1). By varying ϕ_C^{CB} it is possible to simulate some recent measures implemented by central banks that extend the range of possible collaterals.[13]

$LTV_{B,t}^{CB}$ and $LTV_{C,t}^{CB}$ resemble the haircuts applied to the collateral pledged against the credit provided by the central bank to private banks. Although central banks' haircuts are officially fixed, we assume them to be time-varying, since they reflect the underlying risk associated with the collateral. For instance, a downgrading of the eligible collaterals may result in a lower haircut category. Thus, also in this case, the LTV ratios determining the liquidity of the system are endogenized. More specifically, $LTV_{B,t}^{CB}$ and $LTV_{C,t}^{CB}$ are

[13] This analysis is not conducted in the present paper.

expressed in the following way:

$$\frac{LTV_{B,t}^{CB}}{LTV_{B}^{CB}} = \left(\frac{LTV_{B,t-1}^{CB}}{LTV_{B}^{CB}}\right)^{\phi_{LTV_B^{CB}}} \left(\frac{B_t}{Y_t}\kappa_B\right)^{\varphi_{1,B}} \left(\frac{Y_t}{Y}\right)^{\varphi_{2,B}} \exp\left(\varepsilon_t^{LTV_B^{CB}}\right) \tag{39}$$

and

$$\frac{LTV_{C,t}^{CB}}{LTV_{C}^{CB}} = \left(\frac{LTV_{C,t-1}^{CB}}{LTV_{C}^{CB}}\right)^{\phi_{LTV_C^{CB}}} \left(\frac{L_t^C R_t^C}{P_t^H H_t}\kappa_L\right)^{\varphi_{1,C}} \left(\frac{L_t^C}{D_t}\kappa_D\right)^{\varphi_{2,C}} \left(\frac{Y_t}{Y}\right)^{\varphi_{3,C}} \exp\left(\varepsilon_t^{LTV_C^{CB}}\right) \tag{40}$$

where $\kappa_D = \frac{D}{L^C}$, and $\phi_{LTV_B^{CB}}$ and $\phi_{LTV_C^{CB}}$ are autoregressive parameters, $0 < (\phi_{LTV_B^{CB}}, \phi_{LTV_C^{CB}}) < 1$. In (39) and (40) we have that $\varphi_{1,B}, \varphi_{1,C}, \varphi_{2,C} < 0$ and $\varphi_{2,B}, \varphi_{3,C} > 0$. $\varepsilon_t^{LTV_B^{CB}}$ and $\varepsilon_t^{LTV_C^{CB}}$ are i.i.d. shocks with zero mean and standard deviation $\sigma_{LTV_B^{CB}}$ and $\sigma_{LTV_C^{CB}}$, respectively. The same reasoning behind equations (36) and (37) applies here too. Therefore, we assume that the LTV ratio associated with government bonds is a function of the proxies for the systemic risk of the economy, while the LTV ratio relative to loans to households is a function of proxies for both idiosyncratic risk of households and banks, and the systemic risk of the economy.

As in Gerali et al. (2010), the law of motion of equity stock is given by:

$$Z_t = (1-\delta^b)Z_{t-1} + \phi^B \Omega_{t-1}^B \tag{41}$$

where δ^b represents the cost of managing bank capital (it is analogous to the depreciation rate of physical capital), and $(1-\phi^B)$ summarizes the dividend policy of the bank, which is assumed to be exogenous. Financial intermediaries can accumulate net worth only through retained earnings.

By substituting the definition of Z_{t+1} obtained from (34) forwarded one period into (35), the latter boils down to a one-period profits equation, and the maximization problem becomes static. Expected real profits at the end of period t are thus defined as:

$$E_t\left[\frac{\Omega^B_{t+1}}{P_t}\right]=\frac{R^C_tL^C_t}{P_t}+\frac{R^B_tB^B_t}{P_t}-\frac{R^D_tD_t}{P_t}-\frac{Z_t}{P_t}-\frac{R^{CB}_tL^{CB}_t}{P_t}-\frac{e}{2}\left(\frac{w^C_tL^C_t+w^G_tB^B_t}{Z_t}-\nu^b\right)^2\frac{Z_t}{P_t}-\frac{\gamma^C}{2}\left(\frac{L^C_t}{P_t}\right)^2 \tag{42}$$

Banks maximize their profits (42) subject to the balance sheet identity (34) and to the borrowing constraint (38). In order to simplify the maximization problem, we proceed as follows. We isolate B^B_t from equation (34) and substitute for it wherever it appears in the Lagrangian. Since banks behave competitively, they take the path of all the interest rates as given. Thus, the choice variables for banks are the quantities of deposits, loans to households, equity, and loans from the central bank. The first order necessary conditions with respect to deposits, loans to households, equity, and loans from the central bank are the following:

$$R^D_t=R^B_t+\frac{\mu^B_t\phi^{CB}_BLTVC^{CB}_{B,t}}{E_t\left[R^B_{t+1}\pi_{t+1}\right]}-\frac{\varphi_{2,C}L^C_t}{D_t}\frac{\mu^B_t\phi^{CB}_CLTVC^{CB}_{C,t}}{E_t\left[R^C_{t+1}\pi_{t+1}\right]}-w^G_te\left(\frac{w^C_tL^C_t+w^G_tB^B_t}{Z_t}-\nu^b\right) \tag{43}$$

$$\begin{aligned}R^C_t&=R^B_t+\frac{\mu^B_t\phi^{CB}_BLTVC^{CB}_{B,t}}{E_t\left[R^B_{t+1}\pi_{t+1}\right]}-(\varphi_{1,C}+\varphi_{2,C}+1)\frac{\mu^B_t\phi^{CB}_CLTVC^{CB}_{C,t}}{E_t\left[R^C_{t+1}\pi_{t+1}\right]}+\\&+e[w^C_t(1+\varphi_{1,w^C}+\varphi_{2,w^C})-w^G_t]\left(\frac{w^C_tL^C_t+w^G_tB^B_t}{Z_t}-\nu^b\right)+\gamma^CL^C_t\end{aligned} \tag{44}$$

$$\begin{aligned}R^B_t&=1-\frac{\mu^B_t\phi^{CB}_BLTVC^{CB}_{B,t}}{E_t\left[R^B_{t+1}\pi_{t+1}\right]}+\frac{e}{2}\left(\frac{w^C_tL^C_t+w^G_tB^B_t}{Z_t}-\nu^b\right)^2+\\&+eZ_t\left(\frac{w^G_t-\frac{\varphi_{2,w^C}L^C_tw^C_t}{Z_t}}{Z_t}-\frac{w^C_tL^C_t+w^G_tB^B_t}{{Z_t}^2}\right)\left(\frac{w^C_tL^C_t+w^G_tB^B_t}{Z_t}-\nu^b\right)\end{aligned} \tag{45}$$

$$R_t^B = R_t^{CB} + \mu_t^B R_t^{CB} - \frac{\mu_t^B \phi_B^{CB} LTVC_{B,t}^{CB}}{E_t\left[R_{t+1}^B \pi_{t+1}\right]} + w_t^G e\left(\frac{w_t^C L_t^C + w_t^G B_t^B}{Z_t} - \nu^b\right) \tag{46}$$

where μ_t^B is the Lagrange multiplier.

2.5 The Government Sector

The consolidated government-central bank budget constraint is given by:

$$\frac{B_t}{P_t R_t^B} + \frac{M_t}{P_t} + \frac{L_t^{CB}}{P_t} + T_t = \frac{B_{t-1}}{P_t} + \frac{M_{t-1}}{P_t} + \frac{L_{t-1}^{CB} R_{t-1}^{CB}}{P_t} + G_t \tag{47}$$

where B_t is the stock of government interest-bearing debt held by the public ($B_t = B_t^B + B_t^U$), and M_t is the total amount of money held by the public ($M_t = M_t^C + M_t^U$). Government spending, net of interest expenses, G_t follows an AR(1) process:

$$\log\left(\frac{G_t}{G}\right) = \phi_G \log\left(\frac{G_{t-1}}{G}\right) + \varepsilon_t^G \tag{48}$$

where ε_t^G is an i.i.d. shock with zero mean and standard deviation σ_G.

We introduce a passive fiscal policy rule, whereby the total amount of tax collection is a function of total government's liabilities, in order to prevent the emergence of inflation as a fiscal phenomenon, as suggested by Leeper (1991):

$$T_t = \psi_0 + \psi_1 \left[\frac{b_{t-1}}{\pi_t} - \frac{b}{\pi}\right] \tag{49}$$

where ψ_0 is the steady-state level of T_t. Equation (49) indicates that the level of taxes reacts to deviations of the outstanding level of public debt from its steady-state level. In other words, taxes are not allowed to act independently from the stock of government liabilities outstanding in the economy.

Besides providing loans to banks, the monetary authority sets the policy rate, which is assumed to be the rate on central bank's loans to private banks R_t^{CB}, according to the following Taylor (1993) rule:

$$\log\left(\frac{R_t^{CB}}{R^{CB}}\right) = \alpha_R \log\left(\frac{R_{t-1}^{CB}}{R^{CB}}\right) + (1-\alpha_R)\left\{\alpha_\pi \log\left(\frac{\pi_t}{\pi}\right) + \alpha_Y \log\left(\frac{Y_t}{Y}\right)\right\} + \varepsilon_t^R \quad (50)$$

where α_R, α_π, α_Y indicate the response of R_t^{CB} to the lagged policy rate, inflation and output, respectively. Thus, the policy rate is determined by the deviation of inflation and output from the steady-state with an interest rate smoothing component. The monetary policy shock ε_t^R is an i.i.d. with zero mean and standard deviation σ_R.

2.6 The Resource Constraint and Aggregation

The model is completed by specifying the aggregated variables for consumption, money, bonds and taxes:

$$C_t = C_t^C + C_t^U \quad (51)$$

$$M_t = M_t^C + M_t^U \quad (52)$$

$$B_t = B_t^U + B_t^B \quad (53)$$

$$T_t = T_t^C + T_t^U \quad (54)$$

and the resource constraint of the economy:

$$Y_t = C_t + G_t + I_t(1 + AC_t^I) + AC_t^P + \frac{e}{2}\left(\frac{w_t^C L_t^C + w_t^G B_t^B}{Z_t} - \nu^b\right)^2 Z_t + \frac{\gamma^C}{2}\left(L_t^C\right)^2 \quad (55)$$

Total output is allocated to consumption, government spending, investment (comprehensive of capital adjustment costs), price adjustment costs, and a component related to banking sector's frictions.

The model is composed of 43 equations for 43 variables. Since the equilibrium of the model cannot be solved analytically, we log-linearized it around the steady-state. We solved the model using both the MATLAB routine *Gensys* written by Christopher Sims and *Dynare* developed by Adjemian et al. (2011).[14] In what follows, calibration issues are first discussed. We then analyze the properties of the model, highlighting the main results.

2.7 The Calibration

The benchmark model is calibrated to match euro area quarterly data over the decade prior to the crisis of 2008. Table 1 and Table 2 report, respectively, some steady-state values and the chosen calibration values for the standard parameters. Some of the steady-states are obtained from the data, or following previous studies. Output is normalized to 1. In the steady-state, 10 percent of consumption is attributed to constrained households, while 90 percent to unconstrained households (Gerali et al., 2010). The same ratio is assumed for taxes. The aggregate consumption-output ratio has been set to 0.4, and the taxes-output ratio to 0.1972. The ratio of market to non-market activities is set equal to 0.3, whereas the stock of capital-output ratio to 8. The steady-state value of the gross money market rate has been chosen equal to 1.015, which implies a gross inflation rate of around 1.004.

Following Gerali et al. (2010), we set LTV^C at 0.7, a value in line with the evidence for mortgages in the euro area reported by Calza et al. (2007). LTV_B^{CB} is set at 0.9, consistently with the average levels of valuation haircuts applied by the ECB to eligible marketable central government debt instruments. LTV_C^{CB} is assumed to exhibit a lower steady-state value, namely 0.8. We choose a steady-state value for the housing stock

[14] The codes are available upon request as well as the appendices reporting the deterministic steady-state and the log-linearized model.

equal to 1.

Some parameters are chosen following previous studies and their calibrated value is quite standard in the literature. Among them: the elasticity of substitution across goods θ, set equal to 6 (Schmitt-Grohé and Uribe, 2004); the habit formation parameter γ, set equal to 0.7 (Smets and Wouters, 2007); the elasticity of intertemporal substitution σ, set equal to 0.5, which implies a coefficient of relative risk aversion of 2; the depreciation rate of capital δ calibrated to 0.025 (Christiano et al., 2005; Altig et al., 2011), which implies an annual rate of depreciation on capital equal to 10 percent; the share of capital in the production function α, set to 0.36 (Christiano et al., 2005; Altig et al., 2011); the parameter of the price adjustment cost ϕ_P, calibrated to 100 (Ireland, 2004); the elasticity of real money balances χ, set equal to 7; the Frisch elasticity ψ, set equal to 1. The discount factor of constrained and unconstrained households is calibrated to 0.9943 and 0.9923, respectively. The preference parameter of the liquidity aggregator η_x is set at 0.3 in order to pin down a reasonable steady-state level of deposits and money balances of unconstrained households. The share parameter v in the liquidity aggregator index, which indicate the relative share of money in the liquidity bundle, is set equal to 0.2 (Agénor et al., 2012). The parameters of the fiscal and monetary policy rules are calibrated in a standard way, with α_R set equal to 0.7, α_π to 1.5, α_Y to zero, and ψ_1 to 0.3.

The fraction of bank capital reinvested ϕ^B is assumed to be 0.9, while the costs of managing loans to households is chosen equal to 0.01. The cost associated with the leverage requirement is set equal to 0.1 (Gerali et al., 2010).

The AR coefficients and the standard deviations of the shocks are set to $\phi_A = 0.95$, $\phi_G = 0.90$, $\sigma_A = 0.01$, $\sigma_R = 0.005$, $\sigma_G = 0.012$, $\sigma_{PH} = 0.1$ (see, for example, Christiano and Eichenbaum, 1992; Kim, 2000; Andrés et al., 2004; Altig et al., 2011). ϕ_{PH} is set equal to 0.8 after regressing on its first lag actual quarterly data of housing prices in the euro area over the period 2003-2008.

There is little guidance in the literature on how to set the parameters of the LTV ratios and risk weights. Therefore, we adopt the following calibration strategy. We set these parameters so as to match actual correlations among LTV ratios and risk weights, and their determinants. In other words, the correlations of our simulated variables have to be approximately identical to the actual ones reported in Table 3, and calculated using euro area data obtained from the ECB Statistical Data Warehouse and Thomson Reuters Datastream. Table 4 reports the resulting calibration for the parameters. We choose the autoregressive parameters by regressing the actual series of our proxies for the LTV ratios on their first lag. The standard deviations of the shocks to the LTV ratios and risk weights have been set equal to 0.1.

Lastly, the values of the remaining parameters and steady-states are computed using the deterministic steady-state solution.

2.7.1 A Strategy for Modeling the Basel Accords

Thanks to the novel formulation of the weighted leverage cost, the model allows us to distinguish different prudential regulatory regimes by adequately changing capital requirements and risk weight measures. In the baseline calibration of the model, the economy is assumed to be subjected to a regulatory framework similar to *Basel III*. Therefore, we set the steady-state ratio of bank capital Z to total assets $(B^B + L^C)$ at 0.13, the value imposed by *Basel III*. For this purpose, we need to set the cost of managing bank capital δ^b at 0.021. The other regime considered in the analysis (*Basel II*) requires a leverage ratio equal to 0.08, which implies δ^b equal to 0.035.

The parameters of equation (36) and equation (37) are then exploited to further distinguish the different regimes. Besides imposing capital requirements, *Basel II* strengthened the role of systemic risk in comparison with previous regulatory frameworks. Angelini et al. (2010) and Angelini et al. (2012) model a risk-based *Basel II* mechanism by introducing time-varying weights expressed as a function of output deviations from the steady-state. The role played by financial intermediaries in the recent financial crisis reinforced the concerns about the inadequacy of risk measures based solely on countercyclical systemic elements. Therefore, authorities proposed a new regulatory regime, *Basel III*, which in fact considers a wider set of risk-sensitive capital requirements (Basel

Committee and others, 2009; Basel Committee on Banking Supervision, 2010). The new framework emphasizes even more that the amount of capital banks must hold is also determined by the riskiness of each particular borrower. As the risk of a specific asset increases, banks are forced to hold a larger amount of capital (Aguiar and Drumond, 2007). In light of these considerations, and differently from the model by Angelini et al. (2012), our risk weights depend also on the time-varying riskiness embedded in the balance sheet of banks. As a result, our richer setting is able to capture, at least to a first approximation, the broader definition of risk introduced with *Basel III*. In particular, including proxies for counterparties' (i.e. households and government) credit risk is a way to model the interrelationship between risk-perception and the risk weights present in the leverage requirement imposed by regulators on financial intermediaries.

In light of these considerations, the *Basel II* regime is modeled by setting to zero the parameters φ_{1,w^G}, φ_{1,w^C} and φ_{2,w^C}. Lastly, a *No Basel* regime is considered by assuming that risk weights are time-invariant. Table 5 summarizes the calibration strategy chosen for the different regulatory frameworks.

3 The Results

As highlighted in previous sections, the model exhibits a quite high degree of complexity. In order to retain tractability, in this paper we focus on a few set of well-defined issues, leaving for future research the study of further questions that may be potentially tackled using this framework. More precisely, in this paper we first show the implications of having endogenous loan-to-value ratios (paragraph 3.1), and then we compare the effectiveness of different prudential regulatory regimes in affecting business cycle fluctuations and restoring macroeconomic and financial stability (paragraph 3.2).

Table 6 reports the shocks present in the model economy, distinguishing between standard macroeconomic shocks, financial shocks and risk weight shocks. This classification is used extensively in the next paragraphs. Figure 2 reports graphically the main channels at work when the economy is hit by a contractionary monetary policy shock. As it can be easily generalized to other types of disturbances, it will guide us throughout the following pages.

3.1 Exogenous vs Endogenous LTV Ratios

Endogenous and time-varying loan-to-value ratios for households and banks represent one of the salient features of model. Inspired by the empirical evidence, we have derived a novel formulation of LTV ratios that combines both specific risk factors and a countercyclical element. The first issue we need to address regards the implications of the presence of such endogenous constraints for the main dynamics of the model. To this purpose, we report the impulse response functions to standard macroeconomic shocks, comparing the cases of endogenous versus exogenous loan-to-value ratio of households (LTV_t^C).[15] We perform this exercise using the baseline calibration, which reflects, as already mentioned, a *Basel III* scenario. All the impulse response functions reported in the paper represent percentage deviations from the steady-state.

We focus on six main variables: four standard variable that are standard in the literature (total amount of lending to constrained households, lending rate, output and bank equity) and two banking specific variables, which allow us to obtain a deeper insight on the effects of capital regulation on banks' balance sheet. These are the bank leverage, defined as the ratio of assets over equity, and a risk ratio, defined as the ratio of loans to households and bonds held by banks, introduced to better evaluate how the composition of the asset side of banks' balance sheet changes over time.

Figure 3 reports the impulse response functions to a contractionary monetary policy shock. In line with standard DSGE models, an exogenous increase in the policy rate causes a negative effect on investment, which leads to a contraction of output. However, within this setting, we have further channels through which a monetary policy shock propagates to the economy. In particular, we observe a reduction in the total amount of loans to constrained households due to the combined effect of a higher lending rate and lower housing prices. Since banks are subject to a leverage cost, the drop in households

[15] *Exogenous* refers to LTV_t^C following a simple AR process of order 1. In other words, $\varphi_{1,H} = \varphi_{2,H} = \varphi_{3,H} = 0$. The graphs relative to the other shocks and to banking loan-to-value ratios ($LTV_{B,t}^{CB}$ and $LTV_{C,t}^{CB}$) are available upon request.

lending leads banks to increase their holding of government bonds. As a result, the risk ratio exhibits a substantial decrease, whereas bank capital increases by around 0.6 percent.

Visual inspection of Figures 3 also suggests that modeling endogenous variations of $LTV_{C,t}$ (blue dashed line) amplifies the effects of a contractionary monetary policy shock. Worsened economic conditions increase the collateral requirement for constrained households, i.e. their borrowing capacity is reduced. More specifically, downward movements in output, house prices and wages generate an endogenous reduction in the LTV of constrained households, which magnifies the drop in total lending. Thus, these findings show that the model is able to reproduce a realistic situation, in which worsened credit market conditions arise from an endogenous tightening of lending requirements.

Turning to a positive technology innovation (Figure 4), it is possible to observe in both cases an increase in real output and better credit conditions for households due to a lower interest rate on loans. With endogenous collateral constraints, the overall improvement of both households' idiosyncratic conditions and general economic outlook looses the collateral requirement of constrained households, generating a substantially larger increase in the amount of loans provided by banks to households. As a consequence, also the exposure of banks (i.e. ratio risk) exhibits a larger increase. The procyclical dynamics of credit are thus amplified.

Monetary and technology shocks feature procyclical lending, and, therefore, endogenous LTV ratios generate an amplification effect for credit conditions. However, a government spending shock (Figure 5) leads to a general increase in interest rates, which, in turn, causes a fall in loans to households. In this case, lending is anticyclical, and the presence of a time-varying constraint mitigates the negative effect on total loan quantities. In particular, the lower value of the collateral needed by households reflects the overall improvement of the economic conditions following an expansionary fiscal policy shock. The smaller reduction in lending leads to lower volatility also in the asset side composition of banks.

These findings clearly indicate that the presence of endogenous LTV ratios exacerbates the procyclicality of lending conditions, revealing that our model exhibits better business cycle properties compared to similar settings with exogenous LTV ratios. The greater volatility generated within our setting would require in principle incisive countercyclical measures to prevent excessive fluctuations of business cycles. These issues are partially covered in the next paragraphs.

3.2 Comparing *No Basel* with *Basel III*

In this sub-section we compare the results of our baseline model, which reflects a *Basel III* regime, and those obtained from a specification still featuring endogenous constraints, but no capital requirement and risk weight measures (labeled *No Basel*). Figures 6-8 plot the impulse response functions to the three standard macroeconomic shocks. First of all, it should be noted that the difference in the prudential regimes does not reflect any substantial dissimilarity in the response of output. The negligible impact on the macroeconomy is consistent with the findings of other studies (De Walque et al., 2010; Angelini et al., 2010, 2012), and in this model is probably exacerbated by the absence of borrowing firms.

In addition, we find that the presence of a prudential regime like *Basel III* increases the procyclical nature of credit. The procyclicality of risk-based capital regulatory frameworks is well documented in the literature (Aguiar and Drumond, 2007; Angelini et al., 2010; Pariès et al., 2011),[16] and is due to the fact that credit risk itself is procyclical. Our simulated *Basel III* regime amplifies the response of the quantity of total lending to households after a shock in all three cases. By contrast, *Basel III* is effective in dampening the volatility of both the risk- and leverage position of banks in comparison with the *No Basel* regime. Following a contractionary monetary policy shock (Figure 6), the combination of tighter capital requirements and worsening economic conditions (which increases the riskiness of banks' assets) forces banks to reduce their leverage ratio generating a deeper contraction in the loan supply. The resulting reduction in the size of the asset side of banks' balance sheet leads banks to raise aggressively the lending

[16]See Drumond (2009) for a review of the most recent studies.

rate. Higher borrowing costs faced by constrained households contribute eventually to increase banks' net worth. The key role played by time-varying risk weights is confirmed by considering the responses to productivity and government spending shocks (Figure 7 and Figure 8, respectively). In the first case, for instance, improved economic conditions induce risk weights to decline, making loans less risky. In order to meet the required leverage ratio, banks have to further expand loan supply by reducing the interest rate on loans. These findings corroborate the hypothesis that risk-based capital requirements, as those proposed by *Basel III*, sharpen the procyclical nature of credit when the economy is mainly affected by standard macroeconomic shocks. The countercyclical risk weights induce financial intermediaries to hold excessive equity during economic contractions and too less during economic expansions.

We then investigate the properties of the two regulatory frameworks by observing the patterns of the impulse response functions to two financial shocks, namely a credit crunch shock and a negative housing price shock. The first one, adopted following Andrés and Arce (2012), consists in an exogenous shock to the pledgeability ratio LTV_t^C that reduces the borrowing capacity of households. The second shock is an exogenous negative disturbance on house prices: since the real value of houses is used by households as collateral, a decrease in the price of houses leads to a reduction in the quantity of loans that households are able to receive from banks. Thus, the effects of the two shocks are expected to be qualitatively very similar. Figure 9 and Figure 10 report the impulse response functions.

In line with what found for macroeconomic shocks, the volatility of the risk- and leverage position of banks is substantially lower under a *Basel III* regime. However, the other results are in sharp contrast with those obtained observing the economy reacting to standard macroeconomic shocks. In fact, now *Basel III* seems to be capable of mitigating significantly the negative response of both output and lending quantity. The higher capital requirements and the broader set of risk proxies provided for by *Basel III* reduce the negative spillovers from the financial sector to the economy. The intuition is as follows. Unlike standard macroeconomic shocks, financial shocks have a direct impact on the quantity of loans. The immediate reduction of credit to households induces risk weights to decrease, given that the exposure of households and banks decreases and more than offsets the reduction in aggregate output. Since loans are now less risky, to satisfy the imposed capital requirements the reduction of loan supply has not to be as substantial as in the *No Basel* case. The gains from having a mitigated effect on credit is paid for by higher volatility of the interest rate on loans.

Lastly, we compare the standard deviation of the simulated variables of the baseline model and the specification *No Basel*. The third, fifth and seventh columns of Table 7 report the standard deviation ratios of the simulated variables when using, respectively, all the shocks present in the model, only the macro shocks, and only the financial shocks. The numbers are computed as the standard deviation implied by *Basel III* divided by the standard deviation generated by *No Basel*. Thus, a value larger (smaller) than one indicates that the volatility of the simulated variables under the *Basel III* regime is larger (smaller) than that obtained under a *No Basel* framework. The results confirm that when the economy is hit by all the shocks, *Basel III* increases the volatility of lending and output compared with the case without prudential regulations. Not surprisingly, the same considerations hold when the economy is affected only by standard macroeconomic shocks. However, in a situation in which only financial shocks are at work, namely when the economy is in a period of financial stress, *Basel III* is effective in downsizing substantially the volatility of loan quantity and output. The fact that risk-based prudential regulations seem to work properly only during periods of extraordinary financial stress is consistent with the results of Angelini et al. (2012).

3.3 Comparing *Basel II* with *Basel III*

We now compare the baseline regulatory framework *Basel III* with its predecessor *Basel II*, as specified in sub-section 2.7.1. The impulse response functions of the three standard macroeconomic shocks (Figures 11-13) indicate that *Basel III* is able to generate a lower volatility in the risk- and leverage position of banks than *Basel II*. As far as the remaining variables are concerned, the responses of the two regimes are very close and, in the case of a positive technology shock, even amplified under *Basel III*, suggesting that *Basel III* may potentially be more procyclical than *Basel II* during normal times. This can be attributed to the presence of additional risk weight proxies in the *Basel III* specification, which reinforce the fluctuations of risk associated with loans to households.

The ratios of the standard deviation of the simulated variables under the regime *Basel II* with respect to the *No Basel* case are reported in the second, fourth and sixth columns of Table 7.[17] The findings corroborate the idea that, regardless of the type of shocks hitting the economy, *Basel III* amplifies the volatility of loan quantities in comparison with *Basel II*, whereas mitigates the fluctuations in aggregate output and the risk- and leverage position of banks. The magnitude of these differences is nevertheless relatively small.

These results are confirmed, and, to some extent, strengthened when we add to the simulation exercise the two risk weight shocks, which increase exogenously the risk perception of loans to households (w^C) and government bonds (w^G). Table 8 shows the standard deviation ratios of *Basel III* with respect to *Basel II.* As in the previous paragraph, a value larger than unity indicates that the volatility of the simulated variable under *Basel III* is higher than under *Basel II.* The main conclusion that can be drawn from this analysis is that a regulatory regime like *Basel III* seems to be generally more effective than *Basel II* in reducing the volatility of aggregate output and the risk- and leverage position of banks, whereas *Basel II* is able to stabilize more incisively credit fluctuations.

4 Concluding Remarks

This paper provides a new theoretical framework to study the interactions between financial markets and the rest of the economy. The model formalizes the ideas that banking assets are risky and LTV ratios are not constant and depend on systemic factors and leverage conditions of households and banks. Hence, the model is capable of: a) reproducing

[17] The impulse responses to financial and risk weight shocks are not reproduce herein, but are available upon request.

in a realistic way credit procyclical properties; b) analyzing different prudential regulatory frameworks by modifying the configuration of the key parameters and steady-states of the model.

The results of our study indicate that endogenous LTV ratios magnify the effect of procyclical lending, and thus the effects of a simulated credit crunch. We have also shown the implications of different prudential regulatory measures. When standard macro shocks prevail (i.e. in normal times), prudential regulatory frameworks such as *Basel II* and *Basel III* increase the volatility of credit and macroeconomic variables. When financial shocks prevail (i.e. in periods of extraordinary financial stress) *Basel II* and *Basel III* contribute substantially to stabilize credit markets and the overall economy. Moreover, *Basel III* is generally more effective in doing so than *Basel II*. These findings are very important for policy-makers struggling to find effective tools to smooth business cycle fluctuations and restore macroeconomic and financial stability.

References

Adjemian, S., Bastani, H., Juillard, M., Mihoubi, F., Perendia, G., Ratto, M., and Villemot, S. (2011). Dynare: Reference manual, version 4. Dynare Working Papers 1, CEPREMAP.

Adrian, T. and Shin, H. S. (2010a). Financial intermediaries and monetary economics. In Friedman, B. M. and Woodford, M., editors, *Handbook of Monetary Economics*, volume 3, chapter 12, pages 601–650. Elsevier.

Adrian, T. and Shin, H. S. (2010b). Liquidity and leverage. *Journal of Financial Intermediation*, 19(3):418–437.

Agénor, P.-R., Alper, K., and da Silva, L. P. (2012). Capital requirements and business cycles with credit market imperfections. *Journal of Macroeconomics*, 34(3):687–705.

Aguiar, A. and Drumond, I. (2007). Business cycle and bank capital: Monetary policy transmission under the Basel Accords. FEP Working Papers 242, Universidade do Porto, Faculdade de Economia do Porto.

Altig, D., Christiano, L. J., Eichenbaum, M., and Lind, J. (2011). Firm-specific capital, nominal rigidities and the business cycle. *Review of Economic Dynamics*, 14(2):225–247.

Andrés, J. and Arce, O. (2012). Banking competition, housing prices and macroeconomic stability. *The Economic Journal*, IN PRESS.

Andrés, J., López-Salido, J. D., and Nelson, E. (2004). Tobin's imperfect asset substitution in optimizing general equilibrium. *Journal of Money, Credit and Banking*, 36(4):665–690.

Angelini, P., Clerc, L., Cúrdia, V., Gambacorta, L., Gerali, A., Locarno, A., Motto, R., Roeger, W., den Heuvel, S. V., and Vlcek, J. (2011). BASEL III: Long-term impact on economic performance and fluctuations. BIS Working Papers 338, Bank for International Settlements.

Angelini, P., Enria, A., Neri, S., Panetta, F., and Quagliariello, M. (2010). Pro-cyclicality of capital regulation: Is it a problem? How to fix it? Questioni di Economia e Finanza (Occasional Papers) 74, Bank of Italy, Economic Research and International Relations Area.

Angelini, P., Neri, S., and Panetta, F. (2012). Monetary and macroprudential policies. Working Paper Series 1449, European Central Bank.

Angeloni, I. and Faia, E. (2013). Capital regulation and monetary policy with fragile banks. *Journal of Monetary Economics*, 60(3):311–324.

Aoki, K., Proudman, J., and Vlieghe, G. (2004). House prices, consumption, and monetary policy: a financial accelerator approach. *Journal of Financial Intermediation*, 13(4):414–435.

Basel Committee and others (2009). Strengthening the resilience of the banking sector. *Consultative document, BIS*.

Basel Committee on Banking Supervision (2010). *Basel III: International framework for liquidity risk measurement, standards and monitoring*. Bank for International Settlements.

Beau, D., Clerc, L., and Mojon, B. (2012). Macro-prudential policy and the conduct of monetary policy. Working papers 390, Banque de France.

Bernanke, B. and Gertler, M. (1989). Agency costs, net worth, and business fluctuations. *The American Economic Review*, 79(1):14–31.

Bernanke, B. S., Gertler, M., and Gilchrist, S. (1996). The financial accelerator and the flight to quality. *The Review of Economics and Statistics*, 78(1):1–15.

Bernanke, B. S., Gertler, M., and Gilchrist, S. (1999). The financial accelerator in a quantitative business cycle framework. In Taylor, J. B. and Woodford, M., editors, *Handbook of Macroeconomics*, chapter 21, pages 1341–1393. Elsevier.

Calza, A., Monacelli, T., and Stracca, L. (2007). Mortgage markets, collateral constraints, and monetary policy: Do institutional factors matter? CFS Working Paper Series 2007/10, Center for Financial Studies.

Campbell, J. and Cocco, J. (2011). A model of mortgage default. Working Paper 17516, National Bureau of Economic Research.

Canzoneri, M. B., Cumby, R., Diba, B. T., and López-Salido, D. (2008). Monetary aggregates and liquidity in a neo-wicksellian framework. *Journal of Money, Credit and Banking*, 40(8):1667–1698.

Canzoneri, M. B., Cumby, R., Diba, B. T., and López-Salido, D. (2011). The role of liquid government bonds in the great transformation of American monetary policy. *Journal of Economic Dynamics and Control*, 35(3):282 – 294.

Christensen, I. and Dib, A. (2008). The financial accelerator in an estimated New Keynesian model. *Review of Economic Dynamics*, 11(1):155–178.

Christiano, L. J. and Eichenbaum, M. (1992). Current real-business-cycle theories and aggregate labor-market fluctuations. *The American Economic Review*, 82(3):430–450.

Christiano, L. J., Eichenbaum, M., and Evans, C. L. (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, 119(1):1–45.

Christiano, L. J., Motto, R., and Rostagno, M. (2003). The great depression and the Friedman-Schwartz hypothesis. *Journal of Money, Credit, and Banking*, 35(6):1119–1197.

Christiano, L. J., Motto, R., and Rostagno, M. (2008). Shocks, structures or monetary policies? The Euro area and US after 2001. *Journal of Economic Dynamics and Control*, 32(8):2476–2506.

Christiano, L. J., Motto, R., and Rostagno, M. (2010). Financial factors in economic fluctuations. Working Paper Series 1192, European Central Bank.

Christoffel, K., Coenen, G., and Warne, A. (2008). The new area-wide model of the euro area - A micro-founded open-economy model for forecasting and policy analysis. Working Paper Series 944, European Central Bank.

De Walque, G., Pierrard, O., and Rouabah, A. (2010). Financial (in)stability, supervision and liquidity injections: A dynamic general equilibrium approach. *The Economic Journal*, 120(549):1234–1261.

den Heuvel, S. J. V. (2008). The welfare cost of bank capital requirements. *Journal of Monetary Economics*, 55(2):298–320.

Dib, A. (2010). Banks, credit market frictions, and business cycles. Bank of Canada Working Papers 24.

Dixit, A. K. and Stiglitz, J. E. (1977). Monopolistic competition and optimum product diversity. *The American Economic Review*, 67(3):297–308.

Drumond, I. (2009). Bank capital requirements, business cycle fluctuations and the basel accords: a synthesis. *Journal of Economic Surveys*, 23(5):798–830.

Forlati, C. and Lambertini, L. (2011). Risky mortgages in a DSGE model. *International Journal of Central Banking*, 31(1):3228–54.

Galati, G. and Moessner, R. (2012). Macroprudential policy - A literature review. *Journal of Economic Surveys*, pages –.

Gerali, A., Neri, S., Sessa, L., and Signoretti, F. M. (2010). Credit and banking in a DSGE model of the Euro Area. *Journal of Money, Credit and Banking*, 42:107–141.

Gertler, M., Gilchrist, S., and Natalucci, F. M. (2007). External constraints on monetary policy and the financial accelerator. *Journal of Money, Credit and Banking*, 39(2-3):295–330.

Gruss, B. and Sgherri, S. (2009). The volatility costs of procyclical lending standards: An assessment using a DSGE model. IMF Working Papers 09/35, International Monetary Fund.

Iacoviello, M. (2005). House prices, borrowing constraints, and monetary policy in the business cycle. *The American Economic Review*, 95(3):739–764.

Iacoviello, M. and Neri, S. (2010). Housing market spillovers: Evidence from an estimated DSGE model. *American Economic Journal: Macroeconomics*, 2(2):125–64.

Ireland, P. N. (2004). Money's role in the monetary business cycle. *Journal of Money, Credit and Banking*, 36(6):969–83.

Jaffee, D. M. and Russell, T. (1976). Imperfect information, uncertainty, and credit rationing. *The Quarterly Journal of Economics*, 90(4):651–666.

Kim, J. (2000). Constructing and estimating a realistic optimizing model of monetary policy. *Journal of Monetary Economics*, 45(2):329–359.

Kiyotaki, N. and Moore, J. (1997). Credit cycles. *The Journal of Political Economy*, 105(2):211–248.

Lambertini, L., Mendicino, C., and Punzi, M. T. (2011). Leaning against boom-bust cycles in credit and housing prices. Working Papers 201101, Center for Fiscal Policy, Swiss Federal Institute of Technology Lausanne.

Leeper, E. M. (1991). Equilibria under active and passive monetary and fiscal policies. *Journal of Monetary Economics*, 27(1):129–147.

Lombardo, G. and McAdam, P. (2012). Financial market frictions in a model of the Euro area. *Economic Modelling*, 29(6):2460–2485.

Meh, C. A. and Moran, K. (2010). The role of bank capital in the propagation of shocks. *Journal of Economic Dynamics and Control*, 34(3):555–576.

Mendoza, E. G. (2010). Sudden stops, financial crises, and leverage. *The American Economic Review*, 100(5):1941–1966.

Pariès, M. D., Sørensen, C. K., and Rodriguez-Palenzuela, D. (2011). Macroeconomic propagation under different regulatory regimes: Evidence from an estimated DSGE model for the euro area. *International Journal of Central Banking*, 7(4):49–113.

Roger, S. and Vlček, J. (2011). Macroeconomic costs of higher bank capital and liquidity requirements. IMF Working Paper 11/103, International Monetary Fund.

Roger, S. and Vlcek, J. (2012). Macrofinancial modeling at central banks: Recent developments and future directions. IMF Working Papers 12/21, International Monetary Fund.

Rotemberg, J. J. (1982). Monopolistic price adjustment and aggregate output. *The Review of Economic Studies*, 49(4):517–531.

Schmitt-Grohé, S. and Uribe, M. (2004). Optimal fiscal and monetary policy under imperfect competition. *Journal of Macroeconomics*, 26(2):183–209.

Smets, F. and Wouters, R. (2003). An estimated dynamic stochastic general equilibrium model of the Euro area. *Journal of the European Economic Association*, 1(5):1123–1175.

Smets, F. and Wouters, R. (2007). Shocks and frictions in us business cycles: A bayesian DSGE approach. *The American Economic Review*, 97(3):586–606.

Stiglitz, J. E. and Weiss, A. (1981). Credit rationing in markets with imperfect information. *The American Economic Review*, 71(3):393–410.

Taylor, J. B. (1993). Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39:195–214.

Zhang, L. (2009). Bank capital regulation, the lending channel and business cycles. Discussion Paper Series 1: Economic Studies 33, Deutsche Bundesbank, Research Centre.

Tables

Table 1: Steady-state values

Notation	Description	SS values
Y	Output	1
$L/(1-L)$	Ratio of market to non-market activities	0.3
K/Y	Stock of capital-GDP ratio	8
C/Y	Total consumption-GDP ratio	0.4
C^C/Y	Consumption-GDP ratio CH	$0.1 * C$
C^U/Y	Consumption-GDP ratio UH	$0.9 * C$
T/Y	Taxes-GDP ratio	0.1972
T^C/Y	Taxes-GDP ratio CH	$0.1 * T$
T^U/Y	Taxes-GDP ratio UH	$0.9 * T$
R^{CB}	Gross money-market rate	1.015
LTV^C	Loan-to value ratio households	0.7
LTV_B^{CB}	Loan-to value ratio banks - gov. bonds	0.9
LTV_C^{CB}	Loan-to value ratio banks - loans to HH	0.8
H	Stock of housing	1

Notes: CH indicates constrained households; UH indicates unconstrained households.

Table 2: Benchmark calibration of the standard parameters (Basel III)

Notation	Description	Benchmark values
	Preferences and technology	
α	Share of capital in the production function	0.36
β_C	Intertemporal discount factor of CH	0.9943
β_U	Intertemporal discount factor of UH	0.9923
σ	Elasticity of intertemporal substitution	0.5
χ	Elasticity of money demand	7
ψ	Elasticity of labor supply	1
γ	Habit formation	0.7
θ	Elasticity of substitution between varieties of goods	6
ϕ_P	Price adjustment costs	100
v	Elasticity of money in the liquidity aggregator	0.2
η_x	Elasticity of liquidity in the utility function of UH	0.3
	Fiscal and monetary policy	
ψ_0	Fiscal policy constant	0.1972
ψ_1	Fiscal policy response to b	0.3
α_π	Monetary policy response to inflation	1.5
α_Y	Monetary policy response to output	0
α_R	Monetary policy inertia	0.7
	Banking sector	
δ^b	Cost of managing bank capital	0.021
ϕ^B	Profits reinvested in bank capital	0.9
γ^C	Cost of managing loans	0.01
e	Leverage ratio cost	0.1
	Autoregressive parameters	
ϕ_A	Technology shock	0.95
ϕ_G	Government spending shock	0.90
ϕ_{PH}	Housing prices shock	0.80
	Standard deviations	
σ_A	Technology shock	0.01
σ_G	Government spending shock	0.012
σ_R	Monetary policy shock	0.005
σ_{PH}	Housing prices shock	0.1

Notes: CH indicates constrained households; UH indicates unconstrained households.

Table 3: Actual correlations between LTVs and risk weights and their determinants

	LTV_t^C	$LTV_{B,t}^{CB}$	w_t^G	$LTV_{C,t}^{CB}$	w_t^C
P_t^H	0.624	-	-	-	-
$w_t F_t$	0.576	-	-	-	-
Y_t	0.716	0.441	-0.441	0.702	-0.702
B_t	-	-0.286	0.286	-	-
$(L_t^C R_t^C)/P_t^H$	-	-	-	0.578	-0.578
L_t^C/D_t	-	-	-	0.442	-
L_t^C/Z_t	-	-	-	-	-0.208

Sources: Authors' elaborations on data from the ECB Statistical Data Warehouse and Datastream. **Notes:** All the variables are expressed as quarterly percentage changes over the period 2003-2012 (except for $LTV_{B,t}^{CB}$, which is only available from 2008). LTV_t^C is proxied by the opposite of the net percentage of banks reporting a tightening of the loan-to-value ratio of loans for house purchases over the previous quarter (Question 10 of the Bank Lending Survey). w_t^G is proxied by the sovereign CDS spread of Germany. w_t^C is proxied by the net percentage of banks reporting a tightening of collateral requirements for loans for house purchases over the previous quarter (Question 10 of the Bank Lending Survey). $LTV_{B,t}^{CB}$ and $LTV_{C,t}^{CB}$ are the opposite of w_t^G and w_t^C, respectively. P_t^H is residential property prices of new and existing dwellings. w_t is hourly compensation. F_t is total employment in hours. Y_t is GDP at market price. B_t is general government debt. L_t^C is lending for house purchase (over five years). R_t^C is the interest rate on loans for house purchase. D_t is deposit liabilities. Z_t is capital and reserves. For the computation of the correlations, the quantity of housing h_t has been considered fixed.

Table 4: Benchmark calibration of the parameters of LTV ratios and risk weights

Notation	Description	Benchmark values	
		Exog. LTVs	Endog. LTVs
	LTV_t^C		
$\varphi_{1,H}$	Elasticity of LTV_t^C wrt the value of housing	-	0.02
$\varphi_{2,H}$	Elasticity of LTV_t^C wrt to labor income	-	0.02
$\varphi_{3,H}$	Elasticity of LTV_t^C wrt to output	-	2
ϕ_{LTV^C}	AR parameter	-	0.8
	$LTV_{B,t}^{CB}$		
$\varphi_{1,B}$	Elasticity of $LTV_{B,t}^{CB}$ wrt total government debt	-	-0.2
$\varphi_{2,B}$	Elasticity of $LTV_{B,t}^{CB}$ wrt output	-	0.5
$\phi_{LTV_B^{CB}}$	AR parameter	-	0.2
	$LTV_{C,t}^{CB}$		
$\varphi_{1,C}$	Elasticity of $LTV_{C,t}^{CB}$ wrt the ratio value of loans-value of housing	-	-0.01
$\varphi_{2,C}$	Elasticity of $LTV_{C,t}^{CB}$ wrt the loan-to-deposit ratio	-	-0.005
$\varphi_{3,C}$	Elasticity of $LTV_{C,t}^{CB}$ wrt output	-	2
$\phi_{LTV_C^{CB}}$	AR parameter	-	0.8
	Sovereign bond risk w_t^G		
φ_{1,w^G}	Elasticity of w_t^G wrt total government debt	0.25	0.25
φ_{2,w^G}	Elasticity of w_t^G wrt output	-0.5	-0.5
ϕ_{w^G}	AR parameter	0.2	0.2
	Households' loans risk w_t^C		
φ_{1,w^C}	Elasticity of w_t^C wrt the ratio value of loans-value of housing	0.01	0.01
φ_{2,w^C}	Elasticity of w_t^C wrt the loans to capital ratio	0.01	0.01
φ_{3,w^C}	Elasticity of w_t^C wrt output	-2	-2
ϕ_{w^C}	AR parameter	0.8	0.8
	Standard deviations		
σ^{LTV^C}	Shock to LTV_t^C	0.1	0.1
σ^{w^G}	Shock to w_t^G	0.1	0.1

Table 5: Model specifications of the Basel Accords

↶ Regime	$\frac{Z}{L^C+B^B}$	w_t^G		w_t^C		
		φ_{1,w^G}	φ_{2,w^G}	φ_{1,w^C}	φ_{2,w^C}	φ_{3,w^C}
No Basel	No min. req.	x	x	x	x	x
Basel II	0.08	x	✓	x	x	✓
Basel III	0.13	✓	✓	✓	✓	✓

Table 6: Classification of shocks

Macroeconomic shocks		Financial shocks		Risk weight shocks	
ε^A	Technology shock	ε^{LTV^C}	Credit crunch shock	ε^{w^C}	MBS risk shock
ε^R	Monetary policy shock	$\varepsilon^{LTV_B^{CB}}$	Sovereign debt downgrading shock	ε^{w^G}	Sovereign risk shock
ε^G	Government spending shock	$\varepsilon^{LTV_B^{CB}}$	MBS downgrading shock		
		ε^{P^H}	Housing prices shock		

Table 7: Standard deviation of the simulated variables without risk weight shocks

	All shocks		Only macro shocks		Only financial shocks	
Endog. LTVs	BII	BIII	BII	BIII	BII	BIII
L_t^C	1.234	1.327	1.294	1.406	0.772	0.809
L_t^C/B_t^B	1.523	0.901	2.164	1.374	0.490	0.245
$(L_t^C + B_t^B)/Z_t$	0.081	0.045	0.080	0.043	0.003	0.026
Y_t	1.054	1.045	1.011	1.002	0.643	0.561

Notes: Standard deviation ratios of Basel II and Basel III with respect to No Basel (SD_{BII}/SD_{NB}, SD_{BIII}/SD_{NB}).

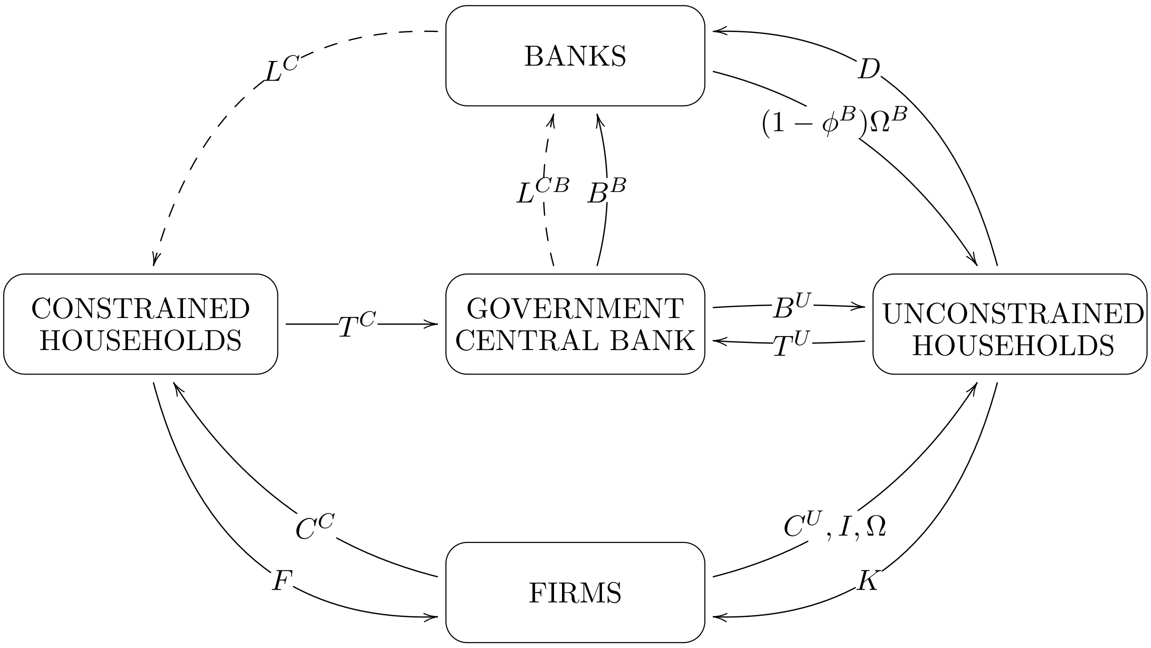
Table 8: Standard deviation of the simulated variables with risk weight shocks

	All shocks	Macro + Weights shocks	Financial + Weights shocks	Only weights shocks
Endog. LTVs	BIII	BIII	BIII	BIII
L_t^C	1.048	1.184	1.020	1.271
L_t^C/B_t^B	0.526	0.673	0.496	0.458
$(L_t^C + B_t^B)/Z_t$	0.519	0.548	0.533	0.517
Y_t	0.982	1.056	0.902	0.947

Notes: Standard deviation ratios of Basel III with respect to Basel II (SD_{BIII}/SD_{BII}).

Figures

Figure 1: Graphical illustration of the main connections of the model



Notes: Dashed arrows indicate connections subjected to borrowing constraints.

Figure 2: The effects of a contractionary monetary policy shock

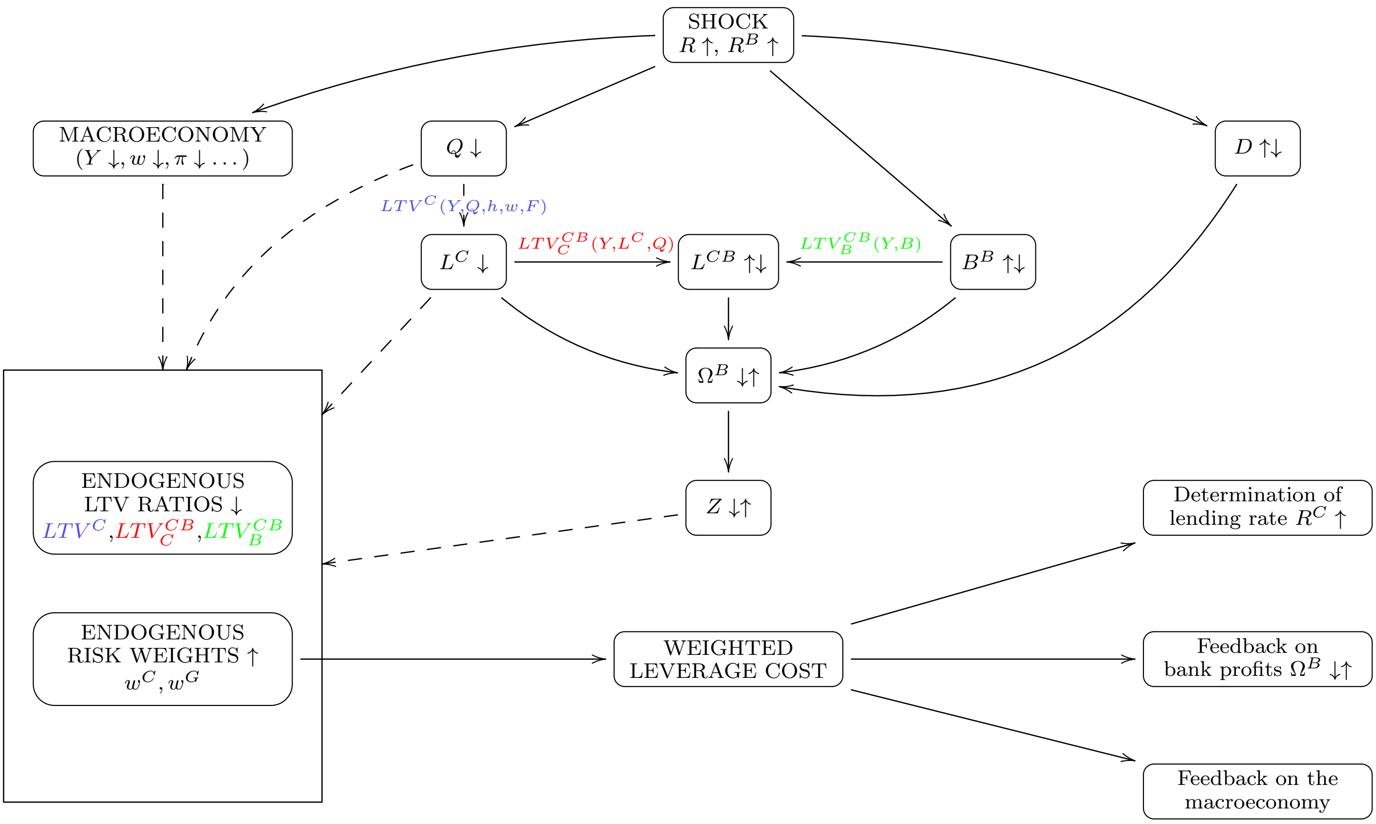


Figure 3: Impulse response functions to a contractionary monetary policy shock

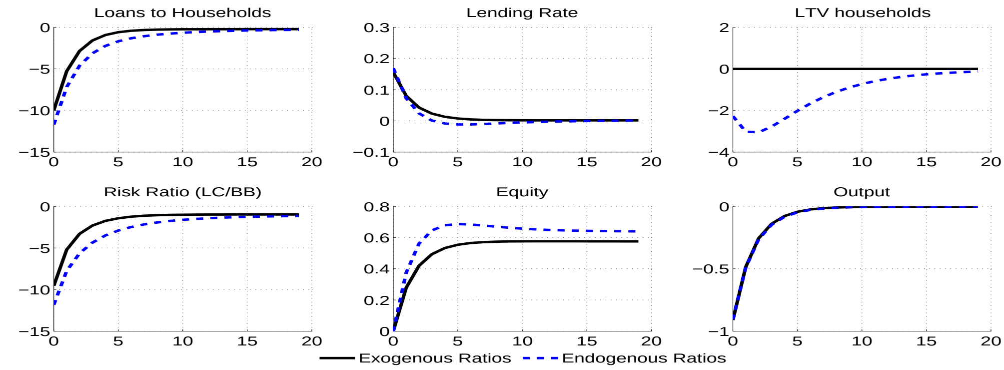


Figure 4: Impulse response functions to a positive technology shock

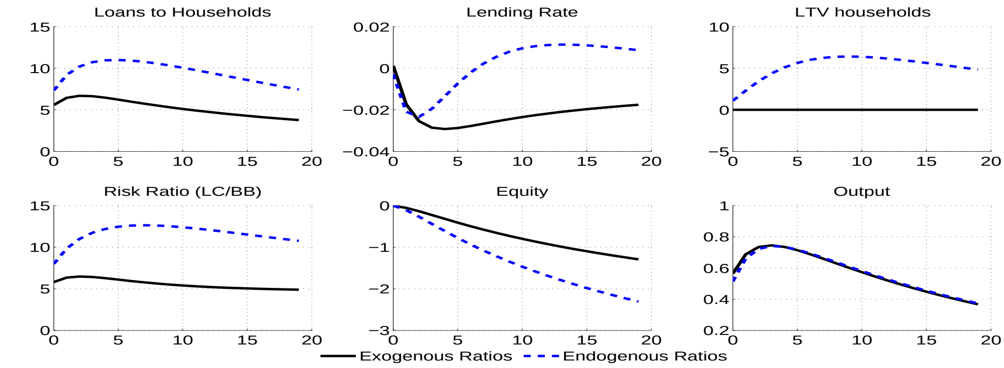


Figure 5: Impulse response functions to a government spending shock

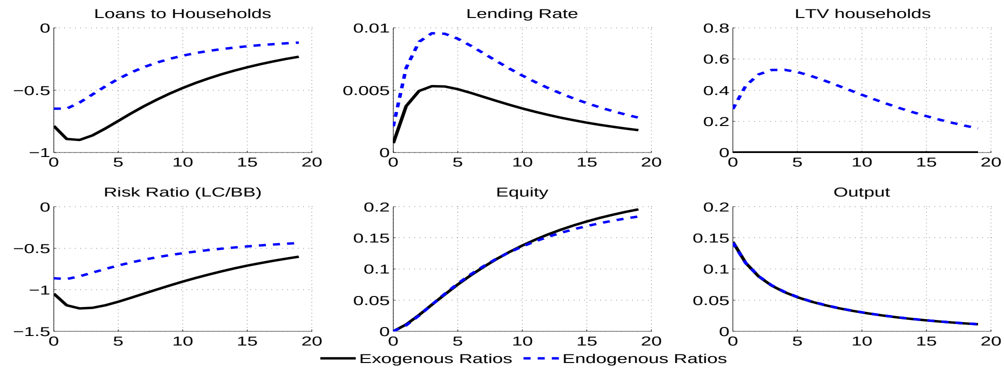


Figure 6: Impulse response functions to a contractionary monetary policy shock

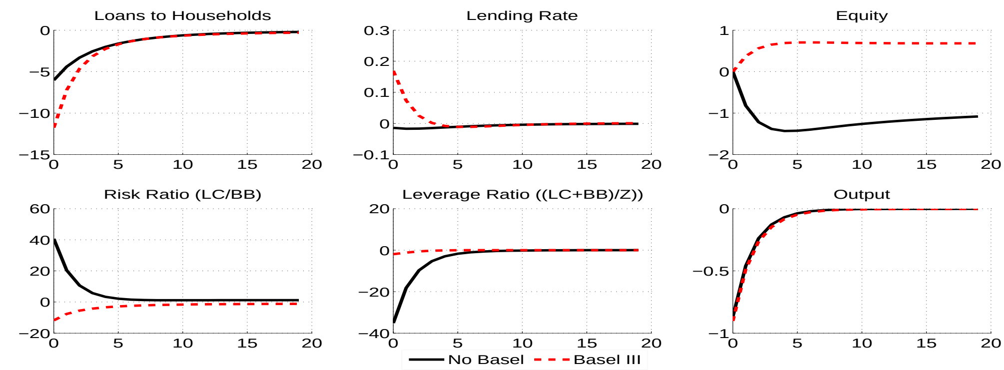


Figure 7: Impulse response functions to a positive technology shock

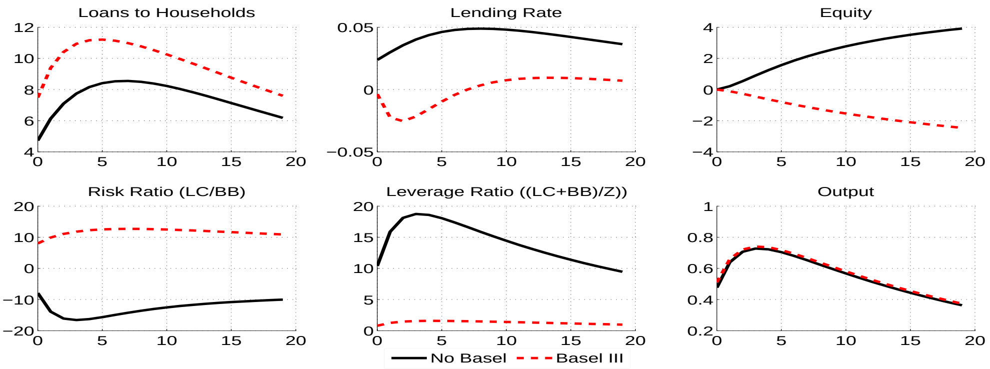


Figure 8: Impulse response functions to a government spending shock

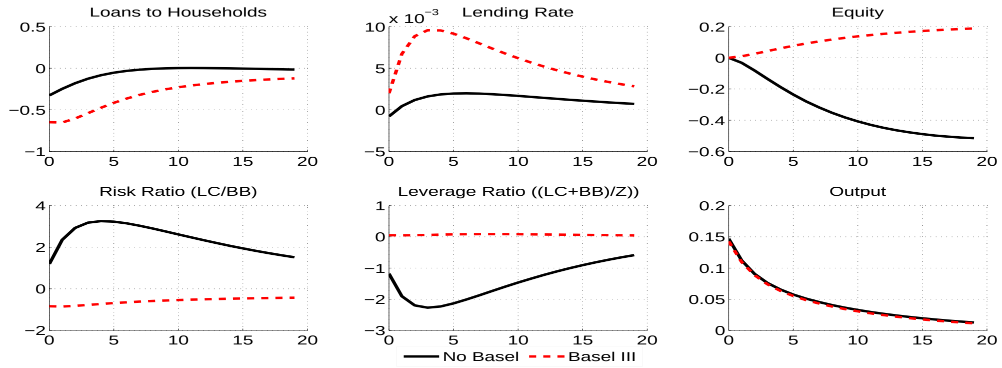


Figure 9: Impulse response functions to a credit crunch shock

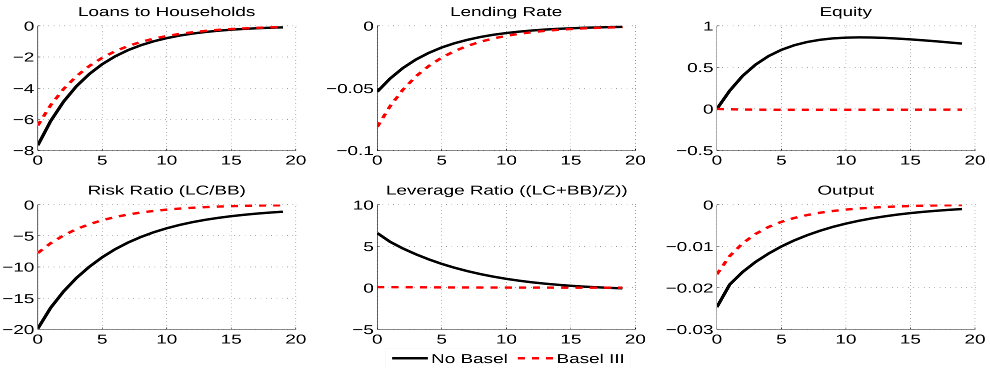


Figure 10: Impulse response functions to negative housing price shock

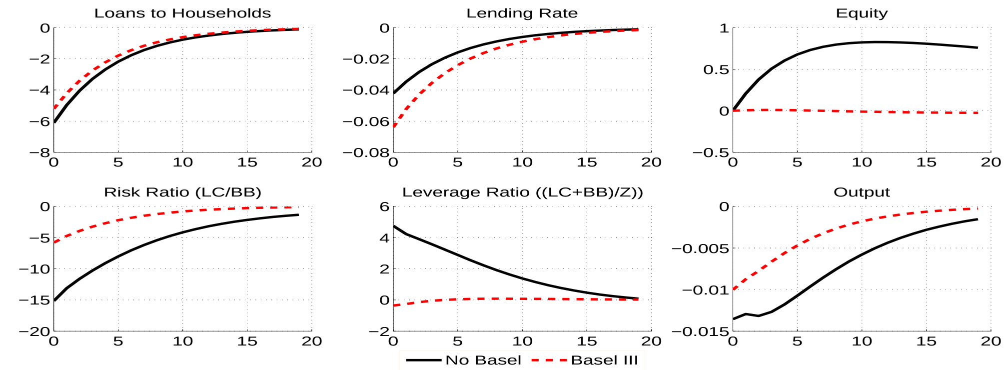


Figure 11: Impulse response functions to a contractionary monetary policy shock

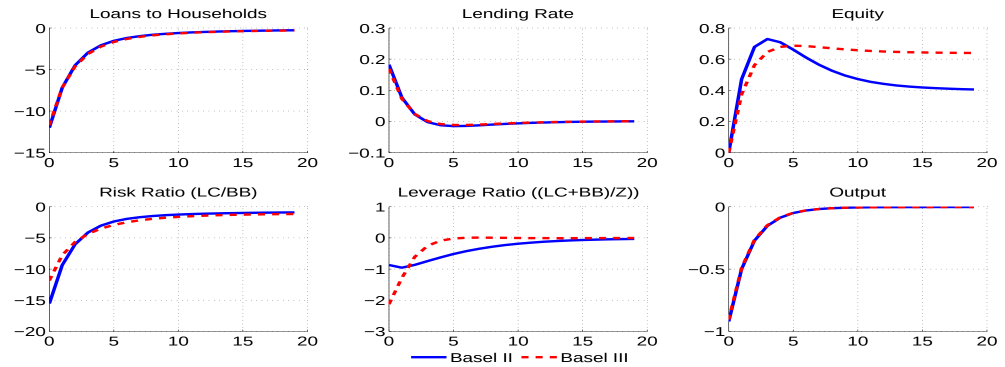


Figure 12: Impulse response functions to a positive technology shock

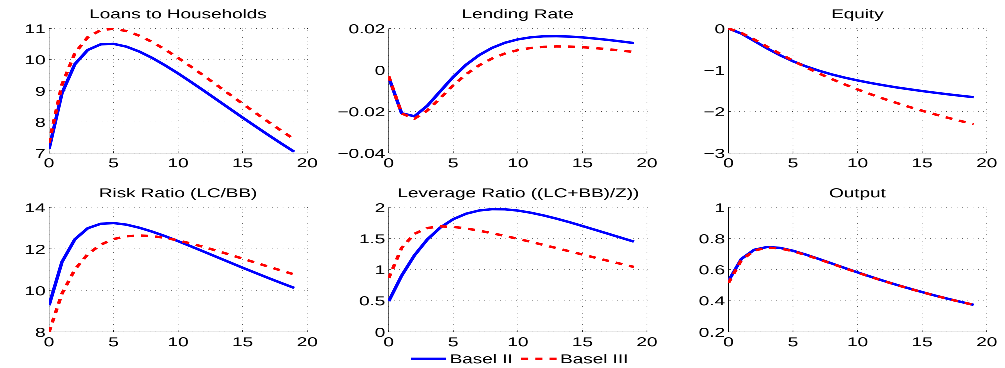
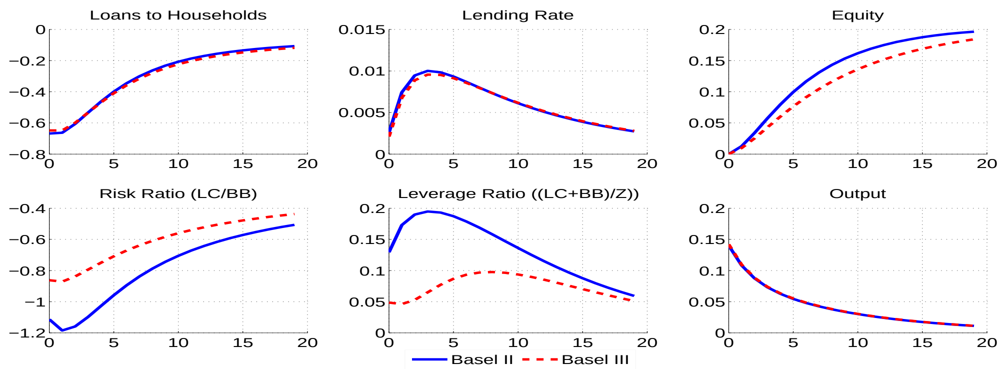


Figure 13: Impulse response functions to a government spending shock



Evaluating Quantitative Easing:
A DSGE Approach

Matteo Falagiarda*
University of Bologna

First version: December 2012
This version: January 2014†

Abstract

This paper develops a simple Dynamic Stochastic General Equilibrium (DSGE) model capable of evaluating the effect of large purchases of treasuries by central banks. The model exhibits imperfect asset substitutability between government bonds of different maturities and a feedback from the term structure to the macroeconomy. Both are generated through the introduction of portfolio adjustment frictions. As a result, the model is able to isolate the *portfolio rebalancing* channel of Quantitative Easing (QE). This theoretical framework is employed to evaluate the impact on yields and the macroeconomy of large purchases of medium- and long-term treasuries recently carried out in the US and UK. The results from the calibrated model suggest that large asset purchases of government assets had stimulating effects in terms of lower long-term yields, and higher output and inflation. The size of the effects is nevertheless sensitive to the speed of the exit strategy chosen by monetary authorities.

KEYWORDS: unconventional monetary policies, quantitative easing, DSGE models, asset prices
JEL Classification: E43, E44, E52, E58

*Department of Economics, University of Bologna. Mail: matteo.falagiarda2@unibo.it Address: Piazza Scaravilli 2 - 40126 Bologna (Italy). Office Phone: +39 051 2092641

†Useful comments have been provided by Dario Bonciani, Jochen Güntner, Richard Harrison, Massimiliano Marzo, Davide Raggi, Luca Sessa and Paolo Zagaglia. I have benefited from conversations with Neil Cabiles, Gabriella Chiesa, Guido Ruta and Alessandro Saia. I also thank participants at seminars at the Department of Economics of the University of Bologna, at the 53rd Annual Conference of the Italian Economic Association, the ADRES Doctoral Conference 2013, the Konstanz Doctoral Workshop on Dynamic Macroeconomics 2013, the Spring Meeting of Young Economists 2013, the European Macroeconomics Workshop 2013, and the 28th Annual Congress of the European Economic Association. Any errors remain my responsibility.

1 Introduction

When an economy is stuck in a liquidity trap or experiences a liquidity shortage, the zero-lower bound (ZLB) of interest rates may challenge the conventional ways of conducting monetary policy.[1] Hence, Quantitative Easing (QE) becomes one of the main tools at the disposal of central banks in order to spur economic recovery. QE can be defined as all policies carried out by central banks involving changes in the composition and/or size of their balance sheet aimed at, in a situation close to the ZLB, easing liquidity and credit conditions with the final goal of stimulating the economic system. There exist therefore a variety of different unconventional measures that fall under the label of QE, such as purchases of treasuries, purchases of private securities, and direct loans to banks, companies and households. Theoretical and practical issues on unconventional monetary policies are discussed in several studies (Krugman, 1998; Svensson, 2003; Bernanke and Reinhart, 2004; Orphanides, 2004; Borio and Disyatat, 2010; Bowdler and Radia, 2012; Joyce et al., 2012). Figure 1 sketches strategies and policy options available to central banks facing ZLB problems as well as the channels through which they may affect aggregate demand.

As the recent global downturn unfolded, many advanced economies experienced a serious liquidity shortage combined with an interest rate close to the ZLB. Thus, their monetary authorities began to pursue QE measures. In particular, in the aftermath of the financial crisis of 2007, interbank money markets froze up due to some important bankruptcies (and, more generally, solvency concerns), a consequent widespread lack of confidence, and coordination failures among market participants. As a result, financial markets also broke down with dramatic consequences for the whole economic system. In an effort to spur economic activity and restore financial market functioning, several central banks intervened by reducing the short-term interest rate. The ZLB quickly became a serious concern for monetary institutions since, in such situations, the availability of credit tends to become irresponsive to quantity of liquidity present in the economic system.

In the US, when Lehman Brothers collapsed, the Fed engaged in dramatic cuts of the policy rate, and the ZLB was virtually reached in December 2008. As Figure 2 shows, this measure was accompanied by a huge expansion of the Fed's portfolio assets, which jumped by over $1,000 billion in a few weeks. Besides rescuing troubled companies, such as Bear Stearns and AIG, the Fed started a much more comprehensive program to provide liquidity and reduce risk premia along the term structure and across a variety of different assets.[2] Given improved conditions in financial markets, many of the programs introduced at the onset of the crisis were suppressed by the end of 2009 or throughout 2010. A second stage of QE, called by practitioners QE2 (in contrast with the first phase QE1), took place from October 2010

[1] The existence of *liquidity traps* was first hypothesized by Keynes (1936), during the years following the onset of the Great Depression, when, in a deflationary situation, short-term nominal interest rates remained for a long time very close to zero.

[2] New specific programs include the Mortgage-Backed Securities (MBS) purchase program, which was intended to help mortgage and housing markets, the Term Asset-Backed Securities Loan Facility, aimed at providing credit to households and small companies, the Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility, which provided funding to banks for their purchase of asset-backed securities, and the Term Auction Facility, which provided term funds to depository institutions.

until June 2011, mainly consisting of purchases of medium- and long-term treasury securities.[3]

In September 2012, Bernanke announced that the Fed will purchase additional agency mortgage-backed securities at a pace of $40 billion per month, and will extend the average maturity of its holdings of securities. These actions are expected to increase the Fed's holdings of longer-term securities by about $85 billion each month until the end of the year. The declared objective of QE3 is to "put downward pressure on longer-term interest rates, support mortgage markets, and help to make broader financial conditions more accommodative." (Board of Governors of the Federal Reserve System, 2012).

The QE approach of the Bank of England (BoE) has been quite different to that implemented by the Fed. As shown in Figure 3, a huge expansion of the balance sheet occurred just after the insurgence of the crisis. During this first stage, the central bank implemented some liquidity support measures, such as extensions to its lending operations, by allowing banks to borrow from a wider-than-normal range of collateral. The second stage of unconventional measures in the UK began with the establishment of the Asset Purchase Facility (APF) fund in March 2009, a separate subsidiary company of the BoE.[4] The goal of the APF was to improve market functioning by injecting money into the economy in the form of purchases of high-quality public and private assets. However, APF's operations were overwhelmingly oriented towards purchases of medium- and long-term governments bonds (Figure 4). Private securities accounted for a tiny proportion of the APF's purchases. Because of further recessionary pressures during the end of 2011, the Bank of England extended the program in October 2011, injecting additional liquidity into the economy, mainly in the form of medium- and long-term gilt purchases. Two more waves of purchases took place in February 2012 and July 2012, bringing the total amount of assets purchased by the BoE to the remarkable value of £375 billion. At the time of writing this paper, a date for a definitive exit strategy is still uncertain.

Recent events have inspired a growing body of empirical literature trying to assess whether unconventional monetary policies have been successful. However, gauging the effects of unconventional monetary policies remains a hard task. The reasons can be found both in the uncertain time lags between actions and effects, and in the difficulties related to disentangling other important factors, especially government policies and international developments. Another empirical concern is the identification of the channels through which QE may affect yields, premia, and other variables of interest. A substantial number of empirical contributions rely therefore on event studies, i.e. they focus on the patterns of specific variables, such as yields, within a narrow time interval between the announcement or the implementation of a policy. Evidence provided by event studies has been generally supportive of the effectiveness of QE policies, both in the US (Klyuev et al., 2009; Blinder, 2010; Neely, 2010; Gagnon et al., 2011; Krishnamurthy and Vissing-Jorgensen, 2011; Swanson, 2011; Glick and Leduc, 2012) and in the UK (Klyuev et al., 2009; Meier, 2009; Joyce et al., 2011b; Glick and Leduc, 2012; Joyce and Tong, 2012).

[3]"QE1 directly supported struggling banks by buying their problematic assets. QE2 supports the government." (Bagus, 2010).

[4]The accounts of the APF are not consolidated with those of the central bank. Therefore, all the operations of the APF fund fall inside the category "other assets" in Figure 3.

Another strand of the empirical literature employs econometric techniques (Gagnon et al., 2011; Meaning and Zhu, 2011; Bridges and Thomas, 2012; D'Amico et al., 2012; Glick and Leduc, 2012; Joyce and Tong, 2012; Kapetanios et al., 2012; Kozicki et al., 2012; Stroebel and Taylor, 2012; Wright, 2012; Baumeister and Benati, 2013; D'Amico and King, 2013), affine term structure models (Christensen and Rudebusch, 2012; Hamilton and Wu, 2012) and other finance models (Doh, 2010; Neely, 2010). These works generally find that the unconventional monetary measures recently taken in the US and in the UK have been effective.

In addition, more or less fully-fledged structural models have been used to assess the impact of unconventional monetary policies.[5] In standard Dynamic Stochastic General Equilibrium (DSGE) models, QE may only work through a *signaling channel*,[6] since the representation of the financial sector is very stylized. In order to capture the effects of QE policies via other channels, it is necessary to depart from the conventional DSGE framework by introducing specific financial frictions and structures.

A first attempt has been made by modeling financial intermediaries and banking frictions, in order to focus on the role of unconventional monetary policies in facilitating lending. These models are able to capture the *credit channel* of QE. Contributions in this area have been produced by Cúrdia and Woodford (2010), Dib (2010), Gertler and Kiyotaki (2010), Brendon et al. (2011), Del Negro et al. (2011), Gertler and Karadi (2011), Hilberg and Hollmayr (2011), Chadha et al. (2012), and Chadha and Corrado (2012).

A different type of DSGE models features imperfect asset substitutability to isolate the *portfolio rebalancing channel* of QE. Within these frameworks, QE measures may affect asset prices and returns by changing the relative supplies of different assets. There has recently been a growing attention towards the contributions by Tobin (1969, 1982) about imperfect asset substitutability, whose portfolio approach has been employed in dynamic optimizing models by Andrés et al. (2004), Marzo et al. (2008), and, more recently, by Falagiarda and Marzo (2012) and Zagaglia (2013). Chen et al. (2012) and Harrison (2012a,b) adopt this framework to study unconventional monetary policies. In models with imperfect asset substitutability, investors tend to rebalance their asset portfolios whenever the supply of the different types of assets changes. Large asset purchases by the central bank vary the relative supply of assets of different maturities, inducing movements in their prices. As a result, aggregate demand may also be influenced.

By embracing this last approach, the present paper develops a DSGE model able to capture the effect of large asset purchases of treasuries by central banks. Partially drawing on Chen et al. (2012) and Harrison (2012a,b), the model is characterized by imperfect asset substitutability and a feedback effect from the term structure to the macroeconomy, both generated through the introduction of portfolio adjustment frictions. In other words, agents pay a cost whenever the relative composition of their portfolio deviates from its steady-state level. The model is therefore capable of isolating a *portfolio rebalancing* channel of QE. By purchasing a particular asset, the monetary authority reduces the amount of that asset held

[5]For a comparison of the different DSGE approaches to QE, see Caglar et al. (2012). A large scale non-DSGE model is used by Chung et al. (2012).

[6]See, for example, Eggertsson and Woodford (2003).

by private agents usually in exchange of risk-free reserves. As a result, the price of that asset increases and the interest rate falls, creating favorable conditions for economic recovery through the traditional monetary transmission mechanisms. Indeed, thanks to the general equilibrium nature of the model, it is possible to assess the effect of this type of QE policies on the macroeconomy as well as on yields.

Differently from Chen et al. (2012) and Harrison (2012a,b), who employ perpetuities as long-term bonds, the model presented in this paper features a secondary market for bond trading, as proposed by Ljungqvist and Sargent (2004), allowing a straightforward treatment of zero-coupon government bonds of different maturities. Moreover, unlike Chen et al. (2012) the present model relies on a representative agent setting, avoiding the troublesome differentiation between restricted and unrestricted agents. A further distinction between Harrison (2012b) and the model proposed in this paper is the absence of portfolio adjustment frictions in the utility function of households. I instead decide to include such costs more plausibly in the budget constraint. In addition, particular attention is paid to the calibration strategy in order to simulate carefully large asset purchase programs. Lastly, an extensive sensitivity analysis is performed to show how the results crucially depend on the key parameters of the model. Due to the novelties introduced, this model is more consistent with reality than the similar settings present in the literature. To the best of my knowledge, this model represents the first attempt to evaluate the effects of large asset purchases within a relatively simple DSGE framework characterized by: a) a representative agent; b) a stylized central bank's balance sheet; c) an endogenous term structure featuring imperfect asset substitutability between zero-coupon government bonds of different maturities.

The theoretical framework is then employed to simulate the impact of large purchases of medium- and long-term treasuries in the US during QE2 (from November 2010 to June 2011 - around $800 billion of purchases - Figure 2), and in the UK during the first phase of the APF program (from March 2009 to January 2010 - around £200 billion of purchases - Figure 3). The results from the calibrated model are realistic and generally consistent with those obtained in the literature using different techniques. Overall, they suggest that large asset purchases of government assets had substantial stimulating effects both in terms of lower long-term yields and higher output and inflation. These effects seem to be generally larger for the UK than the US. This is not surprising, given that the purchases characterizing the phases of QE under consideration have been relatively more remarkable in the UK than in the US. Still, the difference in the effects between the two countries is not as large as previously found in the literature. My preferred model specification indicates that large asset purchases of QE2 in the US had a peak effect on long-term rates in annualized percentage rates of -63 basis points, on the level of real GDP of around 0.92%, and on inflation of 0.37 percentage points. In the UK, the preferred model specification suggests that the first phase of the APF program had a peak effect on long-term rates of -69 basis points, on the level of real GDP of 1.25%, and on inflation of 0.49 percentage points. However, the size of the effects crucially depends on the speed of the exit strategy chosen by monetary authorities and on the degree of substitutability among assets of different maturities.

All in all, the contribution of this paper is twofold. First of all, it provides a new and relatively simple setting through which the effects of large purchases of treasuries by central banks can be evaluated within a microfounded macro framework with optimizing agents. Second, it offers fresh evidence on the potential effectiveness of the recent large asset purchase programs conducted in the US and in the UK.

The remainder of the paper is organized as follows. Section 2 elaborates the model and introduces its key features. Section 3 presents the results from the calibrated model. Section 4 concludes.

2 The Model

A representative agent populates the economy and supplies labor inputs. Monopolistically competitive firms hire labor and capital to produce differentiated goods. The government conducts fiscal and monetary policy. Since the deviations from a canonical DSGE setting concern the households and the government sectors, I start here with their discussion.

2.1 Households

There is a representative household, whose preferences are defined over consumption C_t, real money balances $\frac{M_t}{P_t}$ and labor effort L_t, and are described by the infinite stream of utility:

$$U_t = \sum_{t=0}^{\infty} \beta^t u\left(C_t, \frac{M_t}{P_t}, L_t\right) \tag{1}$$

where β is the intertemporal discount factor. The instantaneous utility function $u\left(C_t, \frac{M_t}{P_t}, L_t\right)$ is given by:

$$u\left(C_t, \frac{M_t}{P_t}, L_t\right) = \frac{(C_t - \gamma C_{t-1})^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} + \frac{1}{1-\chi}\left(\frac{M_t}{P_t}\right)^{1-\chi} - \frac{\Psi}{1+1/\psi} L_t^{1+1/\psi} \tag{2}$$

where γ measures the importance of consumption habits, σ is the elasticity of intertemporal substitution, χ is the elasticity of money demand, and ψ is the Frisch elasticity of labor supply.

In this economy, each agent i can choose the composition of a basket of differentiated final goods. Preferences across varieties of goods have the standard constant elasticity of substitution (CES) form à la Dixit and Stiglitz (1977):

$$C_t = \left[\int_0^1 C_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}} \tag{3}$$

where C_t is the aggregate consumption index of all the differentiated final goods produced in the economy under monopolistic competition. There are j-th varieties of final goods ($j \in [0, 1]$), and θ is the elasticity of substitution between different final goods varieties ($\theta > 1$).

Each agent is subject to the following budget constraint, which incorporates the secondary market for bond trading as in Ljungqvist and Sargent (2004):

$$\frac{B_t}{P_tR_t} + \frac{B^H_{L,t}}{P_tR_{L,t}}(1 + AC^L_t) + \frac{M_t}{P_t} + I_t(1 + AC^I_t) = \frac{B_{t-1}}{P_t} + \frac{B^H_{L,t-1}}{P_tR_t} + \frac{M_{t-1}}{P_t} + w_tL_t + q_tK_t - C_t - T_t \quad (4)$$

Thus, agents allocate their wealth among money holding, accumulation of capital, which is rented to firms at the rental rate q_t, and holding of two types of zero-coupon bonds (B_t and $B^H_{L,t}$), which are purchased by households at their nominal price. They receive rental income q_tK_t, where K_t is capital, wage income w_tL_t, where w_t is the real wage. They also pay a real lump-sum tax T_t. I_t is investment, and P_t is the aggregate price level.

Firms face quadratic adjustment costs of investment as in Kim (2000):

$$AC^I_t = \frac{\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2 \quad (5)$$

The law of motion of capital stock is expressed in the following standard way:

$$K_{t+1} = I_t + (1 - \delta)K_t \quad (6)$$

where δ represents the depreciation rate of the capital stock.

The different zero-coupon government bonds are defined as money-market bonds B_t and long-term bonds $B^H_{L,t}$, whose yields are given, respectively, by R_t and $R_{L,t}$. Money-market bonds are considered as a proxy for 3-month-maturity bonds, and the long-term bonds for 10-year-maturity bonds.[7] The budget constraint incorporates the secondary market for bond trading as proposed by Ljungqvist and Sargent (2004). The strength of this approach is that it allows an explicit and straightforward treatment of assets of different maturities. The left-hand side of the budget constraint follows the usual formulation with bonds priced at their interest rates, since at time t, returns R and R_L are known with certainty and are risk-free from the viewpoint of agents. However, the right-hand side of (4) reveals the presence of the secondary market for bond trading as proposed by Ljungqvist and Sargent (2004), according to which long-term bonds are priced at the money-market rate. Even though these bonds represent sure claims for future consumption, they are subject to price risk prior to maturity. At time $t - 1$, an agent who buys longer-maturity bonds and plans to sell them next period would be uncertain about the gains, since R_t is not known at time $t-1$. As stressed by Ljungqvist and Sargent (2004), the price R_t follows from a simple arbitrage argument, since, in period t, these bonds represent identical sure claims to consumption goods at the time of the end of the maturity as newly issued one-period bonds in period t.

As already mentioned, segmentation in financial markets is obtained by introducing portfolio adjustment frictions, which represent impediments to arbitrage behavior that would equalize asset returns. In particular, it is assumed that the intratemporal trading between bonds of different maturities is costly to

[7]However, when calibrating the model, money-market bonds are assumed to include all government debt instruments with maturity up to one year, whereas long-term bonds government debt instruments with maturity longer than one year (see Paragraph 3.1).

each agent. These bond transaction costs are given by:

$$AC_t^L = \left[\frac{\phi_L}{2}\left(\kappa_L \frac{B_t}{B_{L,t}^H} - 1\right)^2\right] Y_t \tag{7}$$

where κ_L is the steady-state ratio of long-term bond holdings relative to short-term bond holdings $\left(\frac{B_L^H}{B}\right)$. Thus, agents pay a cost whenever they shift the portfolio allocation between short and long maturity bonds. Transaction costs are paid in terms of income and are zero in the steady-state.[8]

The rationale for including portfolio frictions is threefold. First of all, these costs can be viewed as a proxy for the behavior of agents towards liquidity risk (i.e. they rationalize a liquidity premium). The longer the maturity of a bond, the less liquid is considered the asset, and vice versa. Since long-term bonds are perceived as less liquid, there are liquidity costs associated with holding them. In other words, agents perceive longer-maturity assets as riskier, and hence associated with a loss of liquidity compared to the same investment in shorter-term bonds. It follows that, as they purchase longer-term bonds, they hold additional short-term bonds to compensate themselves for the loss of liquidity. Thus, agents self-impose a sort of "precautionary liquidity holdings" on their longer-term investments (Andrés et al., 2004). Another justification for including such portfolio frictions rests on the theory of preferred habitat, according to which agents have preferences over bond maturities (Vayanos and Vila, 2009). Therefore, any deviation from the preferred portfolio allocation is costly to households. Third, these costs can be also considered as proxies for the shares of resources devoted to covering information costs, or simply the costs of managing bond portfolios.

2.1.1 Optimality Conditions

Households maximize their lifetime utility (1) subject to the budget constraint (4) and the capital accumulation equation (6). The first order conditions with respect to consumption, labor, money, money-market bonds, long-term bonds, capital and investment, are respectively given by:

$$(C_t - \gamma C_{t-1})^{-1/\sigma} - \beta\gamma E_t(C_{t+1} - \gamma C_t)^{-1/\sigma} = \lambda_t \tag{8}$$

$$\Psi L_t^{1/\psi} = \lambda_t w_t \tag{9}$$

$$\left(\frac{M_t}{P_t}\right)^{-\chi} + \beta E_t \frac{\lambda_{t+1}}{\pi_{t+1}} = \lambda_t \tag{10}$$

[8] This distinctive formulation resembles those proposed by Andrés et al. (2004), Falagiarda and Marzo (2012) and Harrison (2012a,b).

$$\beta E_t \frac{\lambda_{t+1}}{\pi_{t+1}} = \frac{\lambda_t}{R_t} + \frac{\kappa_L \phi_L \lambda_t Y_t \left(\kappa_L \frac{b_t}{b^H_{L,t}} - 1\right)}{R_{L,t}} \tag{11}$$

$$\beta E_t \frac{\lambda_{t+1}}{\pi_{t+1} R_{t+1}} = \frac{\lambda_t}{R_{L,t}} + \frac{\phi_L \lambda_t Y_t \left(\kappa_L \frac{b_t}{b^H_{L,t}} - 1\right)^2}{2R_{L,t}} - \frac{\kappa_L \phi_L \lambda_t Y_t b_t \left(\kappa_L \frac{b_t}{b^H_{L,t}} - 1\right)}{b^H_{L,t} R_{L,t}} \tag{12}$$

$$\beta(1-\delta)E_t \mu_{t+1} = \mu_t - \lambda_t \left(q_t + \phi_K \left(\frac{I_t}{K_t}\right)^3\right) \tag{13}$$

$$\beta E_t \mu_{t+1} = \lambda_t \left(1 + \frac{3}{2}\phi_K \left(\frac{I_t}{K_t}\right)^2\right) \tag{14}$$

where λ_t and μ_t are the two Lagrange multipliers.

2.2 The Government Sector

The consolidated government-central bank budget constraint is given by:

$$\frac{B_t}{P_t R_t} + \frac{B_{L,t}}{P_t R_{L,t}} + \frac{\Delta_t}{P_t} = \frac{B_{t-1}}{P_t} + \frac{B_{L,t-1}}{P_t R_t} + G_t - T_t \tag{15}$$

where $B_{L,t}$ is the total amount of long-term bonds present in the economy and G_t is government spending. As stressed in the previous paragraph, money-market bonds are considered as a proxy for 3-month-maturity government debt assets, and long-term bonds for 10-year-maturity government debt assets.

Drawing on Harrison (2012b), Δ_t is defined as the change in the central bank balance sheet, equal to money creation and net asset purchases:

$$\frac{\Delta_t}{P_t} = \frac{M_t - M_{t-1}}{P_t} - \left[\frac{B^{CB}_{L,t}}{P_t R_{L,t}} - \frac{B^{CB}_{L,t-1}}{P_t R_t}\right] \tag{16}$$

where $B^{CB}_{L,t}$ is the central bank's holdings of long-term government debt. Thus, the stylized central bank's balance sheet of this model includes long-term treasuries on the asset side and money on the liability side. Central bank's holdings of long-term government bonds are a fraction x of the total amount of long-term bonds present in the economy:

$$B^{CB}_{L,t} = x_t B_{L,t} \tag{17}$$

The remaining proportion of long-term bonds is available to households and is given by:

$$B^H_{L,t} = (1 - x_t)B_{L,t} \tag{18}$$

Thus, asset purchases by the central bank are performed by varying the fraction x_t, which is modeled as a variable following an autoregressive process of order one:

$$\log\left(\frac{x_t}{X}\right) = \phi_x \log\left(\frac{x_{t-1}}{X}\right) + \varepsilon^x_t \tag{19}$$

where X is the steady-state value of the fraction of long-term bonds held by the central bank $\left(\frac{B^{CB}_{L,t}}{B_{L,t}}\right)$, and ε^x_t represents an i.i.d. shock to asset purchases with zero mean and standard deviation σ_X. This means that the central bank holds in the steady-state a quantity of long-term bonds X, and temporary fluctuations around this level are determined by (19). One limitation of this formulation is that it is assumed that the central bank gradually starts decumulating long-term asset holdings from the period after the shock. The persistence of the shock is nevertheless carefully calibrated to mimic different plausible exit strategies conducted by the monetary authority.

Government spending, net of interest expenses, G_t follows an AR(1) process:

$$\log\left(\frac{G_t}{G}\right) = \phi_G \log\left(\frac{G_{t-1}}{G}\right) + \varepsilon^G_t \tag{20}$$

where ε^G_t is an i.i.d. shock with zero mean and standard deviation σ_G.

I introduce the following passive fiscal policy rule, according to which the total amount of tax collection T_t is a function of total government's liabilities:[9]

$$T_t = \psi_0 + \psi_1 \left[\frac{b_{t-1}}{\pi_t} - \frac{b}{\pi}\right] + \psi_2 \left[\frac{b_{L,t-1}}{R_t \pi_t} - \frac{b_L}{R\pi}\right] \tag{21}$$

where ψ_0 is the steady-state level of T_t, and b_t and $b_{L,t}$ denote the real stock of short- and long-term bonds ($b_t = B_t/P_t, b_{L,t} = B_{L,t}/P_t$). Equation (21) suggests that the level of taxes reacts to deviations of the outstanding level of public debt from its steady-state level. In other words, taxes are not allowed to act independently from the stock of government liabilities outstanding in the economy.[10]

The central bank is the institution devoted to set the money-market rate R_t, according to the following Taylor (1993) rule:

$$\log\left(\frac{R_t}{R}\right) = \alpha_R \log\left(\frac{R_{t-1}}{R}\right) + (1 - \alpha_R)\left\{\alpha_\pi \log\left(\frac{\pi_t}{\pi}\right) + \alpha_Y \log\left(\frac{Y_t}{Y}\right)\right\} + \varepsilon^R_t \tag{22}$$

where α_R, α_π, α_Y indicate the response of R_t with respect to lagged R_t, inflation and output. Thus, the

[9]In such a way, it is possible to prevent the emergence of inflation as a fiscal phenomenon (Leeper, 1991).

[10]A similar formulation has been employed, for instance, by Schmitt-Grohé and Uribe (2007).

policy rate is determined by the deviation of inflation and output from their steady-state values with an interest rate smoothing component. The monetary policy shock ε_t^R is an i.i.d. with zero mean and standard deviation σ_R.

Finally, the supply of long-term bonds is assumed to follow a simple exogenous AR process, as in Zagaglia (2013):

$$\log\left(\frac{b_{L,t}}{b_L}\right) = \phi_{BL}\log\left(\frac{b_{L,t-1}}{b_L}\right) + \varepsilon_t^{BL} \tag{23}$$

where ε_t^{BL} is a disturbance term with zero mean and standard deviation σ_{BL}. Thus, asset purchase shocks are assumed to affect only the composition of outstanding government liabilities.

2.3 Firms

The final step is to model the firms' sector, which follows a quite standard representation. Each firm j produces and sells differentiated final goods in a monopolistically competitive market. The production function is a standard Cobb-Douglas with labor and capital:

$$Y_t = A_t K_t^{\alpha} L_t^{1-\alpha} - \Phi \tag{24}$$

where α is the share of capital used in production, and Φ is a fixed cost to ensure that profits are zero in the steady-state. A_t is technology and follows an AR(1) process:

$$\log\left(\frac{A_t}{A}\right) = \phi_A \log\left(\frac{A_{t-1}}{A}\right) + \varepsilon_t^A \tag{25}$$

where ε_t^A is an i.i.d. shock with zero mean and standard deviation σ_A.

Firms' optimizing process is constrained by nominal rigidities à la Rotemberg (1982), i.e. firms face quadratic price adjustment costs:

$$AC_t^P = \frac{\phi_P}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \pi\right)^2 Y_t \tag{26}$$

Given the standard CES setting of equation (3), the demand function faced by each single firm j is:

$$Y_t(j) = \left[\frac{p_t(j)}{P_t}\right]^{-\theta} Y_t \Longrightarrow P_t(j) = \left[\frac{Y_t(j)}{Y_t}\right]^{-\frac{1}{\theta}} P_t \tag{27}$$

Thus, the demand function for each single good j is proportionally related to the general output level of the economy, and negatively to the price of good j.

Following Kim (2000), the profit function for each firm j is:

$$P_t\Pi_t(j) = P_t(j)Y_t(j) - w_t L_t(j) - P_t q_t K_t(j) - P_t AC_t^P \tag{28}$$

After employing (26) and (27) into (28), the maximization problem of each firm becomes fully dynamic: each firm maximizes the expectation of the discounted sum of profit flows, given the information at time 0:

$$\Pi_0(j) = E_0\left[\sum_{t=0}^{\infty} \rho_t P_t \Pi_t(j)\right] \tag{29}$$

where ρ_t is a stochastic pricing kernel for contingent claims, i.e. the discount factor of firms. Assuming that each agent in the economy has access to a complete market for contingent claims, the discount factors of households and firms are equal:

$$E_t\frac{\rho_{t+1}}{\rho_t} = E_t\beta\frac{\lambda_{t+1}}{\lambda_t} \tag{30}$$

Therefore, the necessary first order conditions of the maximization problem with respect to labor and capital are given respectively by:

$$w_t = (1-\alpha)\left(\frac{Y_t+\Phi}{L_t}\right)\left(1-\frac{1}{e_t^Y}\right) \tag{31}$$

$$q_t = \alpha\left(\frac{Y_t+\Phi}{K_t}\right)\left(1-\frac{1}{e_t^Y}\right) \tag{32}$$

where e_t^Y is the output demand elasticity:

$$\frac{1}{e_t^Y} = \frac{1}{\theta}\left\{1-\phi_P(\pi_t-\pi)\pi_t+\beta\phi_P E_t\left[\frac{\lambda_{t+1}}{\lambda_t}(\pi_{t+1}-\pi)\pi_{t+1}^2\frac{Y_{t+1}}{Y_t}\right]\right\} \tag{33}$$

which measures the gross price markup over marginal cost. It is easy to check that manipulations of the log-linearized version of (33) lead to the standard New Keynesian Phillips curve.

2.4 The Resource Constraint

The model is completed by specifying the resource constraint of the economy:

$$Y_t = C_t + G_t + I_t(1+AC_t^I) + AC_t^P + \frac{b_{L,t}^H}{R_{L,t}}(AC_t^L) \tag{34}$$

The total output of the economy is allocated to consumption, government spending, investment (comprehensive of capital adjustment costs), price adjustment costs, and a component related to bond adjustment frictions.

2.5 Asset Markets: No Arbitrage and the Feedback

In order to appreciate the main features of the model, a deeper analysis of the asset market's structure is required. Combining the log-linearized version of the two first-order conditions for bond holdings, i.e. equations (11) and (12), yields:

$$\tilde{R}_{L,t} = \tilde{R}_t + A_1 E_t \tilde{R}_{t+1} + A_2 E_t \tilde{\lambda}_{t+1} - A_3 E_t \tilde{\pi}_{t+1} - \phi_L A_4 [\tilde{b}_t - \tilde{b}^H_{L,t}] \tag{35}$$

where A_ι ($\iota = 1, 2, 3, 4$) are convolutions of the parameters. Equation (35) reveals that the long-term rate depends positively on the volume of long-term bonds held by private households, as desired, and negatively on the volume of short-term bonds, because of the imperfect substitutability between the two assets. Thus, asset purchases carried out by the monetary authority, by reducing the supply of long-term bonds at the disposal of households, would lead to a reduction in the long-term yield, as stated by the *portfolio rebalancing* channel of QE. Conversely, an increase in the relative supply of the more illiquid asset (i.e. long-term bond) will bid up the spread between the more illiquid asset and the more liquid asset. The intuition is that to get agents to accept the fact of holding a larger (smaller) fraction of short-term bonds in their portfolio the spread between the two rates has to decrease (increase). Notice the role of the transaction costs parameter ϕ_L that, by generating impediments to the arbitrage behavior of agents that would equalize returns, determines the degree to which relative bonds holding movements affect the long-term rate. When financial frictions are equal to zero, equation (35) boils down to the more usual formulation:

$$\tilde{R}_{L,t} = \tilde{R}_t + A_1 E_t \tilde{R}_{t+1} + A_2 E_t \tilde{\lambda}_{t+1} - A_3 E_t \tilde{\pi}_{t+1} \tag{36}$$

in which a sort of expectations hypothesis holds, and the long-term rate is not affected by changes in the relative holdings of bonds of different maturities.

An additional crucial feature of the model is the presence of a feedback channel from the term structure to the macroeconomy. This can be observed by combining the log-linearized version of the first order conditions for consumption (8) and short-term bonds (11), in order to obtain the Euler equation for consumption, and employing then the first order condition of long-term bonds (12):

$$\tilde{c}_t = A_5 E_t \tilde{c}_{t+1} + A_6 E_t \tilde{\pi}_{t+1} + \cdots - A_7 \tilde{R}_t - A_8 \tilde{R}_{L,t} \tag{37}$$

where A_ι ($\iota = 5, 6, 7, 8$) are convolutions of the parameters. Aggregate demand and, through general equilibrium forces, all the macro variables are therefore affected by the entire simple term structure of interest rate present in this model, and not only by the short-term rate as in standard DSGE frameworks.

The whole story behind the model can be summarized as follows. Long-term bond purchases by the central bank alter the volumes of assets of different maturities, and hence returns (equation (35)), which, in turn, stimulate the economy through standard general equilibrium mechanisms (equation (37)).

3 The Results from the Calibrated Model

The model is employed to simulate the effects of specific QE programs in the US and in the UK. More specifically, I focus my attention on QE2 in the US (from November 2010 to June 2011 - around \$800 billion of purchases), and the first phase of the APF operations in the UK (from March 2009 to January 2010 - around £200 billion of purchases). As already mentioned, both phases were characterized exclusively by purchases of medium- and long-term government securities (Figure 2 and Figure 3). Therefore, it is possible to assess their effects using the model proposed in this paper. I simulate the impact of such programs using a calibrated version of the model.

Since the model cannot be solved analytically, I log-linearized it around the steady-state. I solved the model using both the MATLAB routine *Gensys* written by Christopher Sims, and *Dynare* developed by Adjemian et al. (2011).[11] In what follows, calibration issues are first discussed. I then analyze the results of the baseline model. Lastly, a sensitivity analysis is performed, exploring the effects of varying the key parameters of the model.

3.1 The Calibration

The benchmark model is calibrated to match quarterly data over the most recent period prior to the financial crisis of 2008. Table 1 and Table 2 report, respectively, some steady-state values and the chosen calibration values for the standard parameters. Some parameters are chosen following previous studies and their calibrated value is quite standard in the literature. Among them: the elasticity of substitution across goods θ, set equal to 6 (Schmitt-Grohé and Uribe, 2004); the habit formation parameter γ, set equal to 0.7 (Smets and Wouters, 2007); the elasticity of intertemporal substitution σ, set equal to 0.5, which implies a coefficient of relative risk aversion of 2; the depreciation rate of capital δ calibrated to 0.025 (Christiano et al., 2005; Altig et al., 2011), which implies an annual rate of depreciation on capital equal to 10 percent; the share of capital in the production function α, set to 0.36 (Christiano et al., 2005; Altig et al., 2011); the parameter of the price adjustment cost ϕ_P, calibrated to 100 (Ireland, 2004); the elasticity of real money balances χ, set equal to 7 (Marzo et al., 2008); the Frisch elasticity ψ, set equal to 1.

The parameters of the fiscal and monetary policy rules are calibrated in a standard way, with the exception of α_R, which is chosen very close to one, in order to prevent the short-term rate from responding to inflation/output changes (reflecting a situation close to the ZLB), and, at the same time, to avoid indeterminacy.

[11]The codes are available upon request as well as the appendices reporting the deterministic steady-state and the equations of the log-linearized model.

The AR coefficients and the standard deviations of the shocks are set to $\phi_A = 0.95$, $\phi_G = \phi_{BL} = 0.90$, $\sigma_A = \sigma_{BL} = 0.01$, $\sigma_R = 0.005$, $\sigma_G = 0.012$ (see, for example, Christiano and Eichenbaum, 1992; Kim, 2000; Andrés et al., 2004; Altig et al., 2011; Falagiarda and Marzo, 2012; Zagaglia, 2013).

Some of the steady-states are obtained from the data, or following previous studies. Output is normalized to 1. The consumption-output ratio has been set to 0.57. The share of the representative household's time endowment spent on paid work is set equal to 0.3. The steady-state value of the money-market rate has been chosen identical for both countries, given the very similar recent trends of rates in the US and the UK, obtained from the Federal Reserve Economic Data and the Bank of England Statistical Interactive Database.

In order to simulate accurately the unconventional programs under consideration, the parameters and steady-states related to the new mechanisms proposed in this paper should be carefully chosen. Their values, reported in Table 3, are country-specific and significantly influence the impact of asset purchase policies. The ratio of total debt to GDP, the ratio of debt at different maturities to total debt, and the proportion of long-term debt held by households and the central bank, are obtained by combining data from the OECD Statistical Database, the Federal Reserve Statistical Release, the Bank of England Statistical Interactive Database, and the Bank of England APF Gilt Operational Results Dataset, and taking their values as they were just before the asset purchase shock occurred. In particular, the total debt on GDP ($B + B_L$) is the ratio of the total amount of marketable government debt to GDP. Short-term debt (B) includes money-market instrument plus bonds with maturity up to one year. Long-term debt (B_L) is calculated by subtracting the amount of short-term debt from the total amount of debt.[12]

Also, the standard deviation of the asset purchase shock and the approximated duration of the shock should be carefully set. The magnitude of the asset purchase shock has been chosen equal to 1 for the US (i.e. there has been an increase of 100% in the long-term bonds held by the Fed during QE2), and 12 for the UK (i.e. the BoE increased its holding of long-term treasuries by 1200% during the first stage of the APF operations).[13] The duration of the asset purchase shock is approximated to be three quarters in the US, and four quarters in the UK.

The two *free* parameters of the model, namely the persistence of the asset purchase shock ϕ_x and the parameter of bond adjustment frictions ϕ_L, are not easily quantified. They are set equal, respectively, to 0.83, reflecting a medium-term exit strategy from QE (approximately six years after the asset purchase shock), and 0.01, i.e. 1% of agents' income is devoted to paying portfolio transaction costs. This calibration is similar to that in Chen et al. (2012) (0.015), but diverges from those proposed by Andrés et al. (2004) (0.045), Harrison (2012a) (0.1), and Harrison (2012b) (0.09). I set a lower value for ϕ_L due to the peculiar specification of portfolio adjustment costs in (7), which, being paid in terms of household's income, assume a slightly different interpretation with respect to the works mentioned above. In the next paragraphs some sensitivity analysis on these parameters is conducted.

[12]A debatable assumption behind this calibration strategy is that the two countries were in the steady-state when their central banks intervened.

[13]See Figure 2 and Figure 3.

Finally, the values of the remaining parameters and steady-states are computed using the deterministic steady-state solutions.

3.2 The Impact of Asset Purchases

The model impulse responses to an asset purchase shock are shown in Figure 5 for the US and in Figure 6 for the UK. The impulse response functions are shown as percentage deviations from the steady-state. The simulated asset purchase shock in the US lasts for three quarters and its magnitude is such that central bank's long-term bond holdings double (left upper panel in Figure 5). This reduces the amount of long-term bonds at the disposal of households by around 23 percent, a figure in line with the empirical evidence. The reduction in long-term bond supply pushes down the long-term rate by 47 basis points. Through the feedback mechanisms from the term structure to the macroeconomy, output and inflation experience a substantial increase of 0.69 percent and 0.28 percent, respectively. Notice that the term premium decreases almost as much as the long-term rate, given that the short-term rate, being constrained at the ZLB, does not move substantially.[14]

Figure 6 shows that the asset purchase shock in the UK takes place over four quarters and leads to an increase of 1200 percent of long-term bonds held by the central bank. As a result, long-term government bonds held by households decrease by approximately 27 percent, leading to a reduction in the long-term rate of 69 basis points. The positive effect on the macroeconomic variables is 1.25 percent for output and 0.49 percent for inflation.

Table 4 and Table 5 summarize these findings in annualized percentage rates in the *Baseline* row of *My calibrated model*, reporting also analogous results obtained by previous studies using different techniques. The results obtained from the calibrated version of the model proposed in this paper are quite consistent with what has been previously found in the literature. More precisely, for the US the effect on long-term yield, output and inflation seems to be slightly larger than that obtained in other studies, whereas for the UK a bit smaller. A comparison with Harrison (2012a), who employs a similar DSGE model, reveals that the results of the present model are closer to the empirical evidence coming from empirical studies, especially as far as inflation is concerned. A substantial part of the differences between my results and those found by Chen et al. (2012) and Harrison (2012a) can be ascribed to the presence of the budget constraint with secondary market, which generates higher effects on output and inflation in response to an asset purchase shock.[15]

Not surprisingly, given the different amount of assets purchased, the overall effect of large asset purchases on the economy is found to be larger in the UK than in the US. However, this difference is not as large as previously found in the literature.

[14]The term premium ξ_t is calculated as follows: $\xi_t = R_{L,t} - \frac{1}{N}\sum_{j=0}^{N-1} E_t R_{t+j}$ Thus, the term premium represents deviations of the long-term yield $R_{L,t}$ from the level consistent with the expectations hypothesis. It is assumed that the short-term rate R_t is a proxy for the 3-month yield and the long-term rate $R_{L,t}$ for the 10-year rate. This implies that $N = 40$.

[15]The graphs regarding the model without the budget constraint with secondary market are available upon request from the author.

In order to gain intuition about some of the key mechanisms at work in the model, it is useful to carry out a sensitivity analysis exercise. In particular, in what follows I analyze what happens when changing, first, the persistence of the asset purchase shock ϕ_x, and then the parameter relative to the portfolio adjustment frictions ϕ_L.

3.2.1 Sensitivity Analysis: The Role of the Persistence of the Asset Purchase Shock

In the benchmark calibration, it has been arbitrarily assumed that central banks, after purchasing long-term assets, undertake a medium term exit strategy, i.e. they wind down the program over the following six years by selling the assets accumulated during the QE phases. To illustrate how results change when varying the length of the exit strategy, Figure 7 and Figure 8 plot the impulse response functions considering three different values of ϕ_x: the benchmark value (red line), a higher ϕ_x (0.88), which reflects a longer exit strategy from QE of approximately eight years (green line), and a lower ϕ_x (0.76), which corresponds to a faster exit strategy of around four years (blue line).

When the parameter relative to the persistence of the asset purchase shock ϕ_x increases, the persistence of the response of the long-term yield increases as well, both for the US and the UK, while the magnitude of the response does not change significantly. Importantly, as for the macroeconomic variables, not only the persistence of their response goes up, but also their impact effect. By contrast, a faster exit strategy is associated with a lower effect on the macroeconomy. This is completely in line with what is actually expected, since a longer exit strategy is likely to exert larger inflationary pressures, and a too fast exit strategy to have instead marginal effects on the economy. The reason for that is the presence of nominal rigidities, which lead firms to move their prices more (less) aggressively in response to a more (less) persistent shock (Chen et al., 2012).

Moreover, inflation responds more strongly than output to changes in the length of the policy, a fact consistent with the findings of Chen et al. (2012), and due to the presence, again, of nominal rigidities such as price stickiness. In particular, when prices are more (less) flexible, one would expect a higher (lower) response of inflation to asset purchase shocks. Chen et al. (2012) note that "... higher price flexibility shifts the adjustment in response to asset purchase programs from GDP growth to inflation, by making its process more front-loaded."[16]

The quantitative effects of the simulated asset purchase shock in annualized percentage rates for the different persistence values are reported in Table 4 and Table 5. For the US, the effect on output is in the range of 0.66%-1.27%, while the effect on inflation is found to be in the range 0.23%-0.59%. For the UK, the effect on output is found to lie between 0.94% and 1.61%, and that on inflation between 0.30% and 0.73%. While these findings confirm that the effectiveness of such unconventional monetary policies seems to have been more pronounced in the UK than in the US, they also highlight that their predictions are subject to the uncertainty associated with the timing of the exit strategy from QE chosen

[16]A sensitivity analysis specifically conducted on ϕ_P confirms this statement. The graphs have not been reported for the sake of space, but are available from the author upon request.

by the monetary authority.

3.2.2 Sensitivity Analysis: The Role of Financial Frictions

As already noted, the magnitude of ϕ_L measures the extent of the impediments to the arbitrage behavior of agents, and therefore the degree of imperfect asset substitutability between short- and long-term bonds. Figure 9 and Figure 10 report the impulse response functions for the baseline case (red line), and the cases with higher (0.02) and lower (0.005) portfolio adjustment costs (green and blue line, respectively).

As expected, higher frictions generate larger obstacles to the arbitrage behavior of investors, making the two assets less substitutable. As a result, changes in the relative quantities of bonds held by households lead to a higher responsiveness of long-term yield. The macroeconomic effects are also amplified when ϕ_L increases, and vice versa. UK variables seem to be less sensitive to changes in the parameter ϕ_L in comparison with the US. A specific sensitivity exercise, whose results are not reported here, shows that this is due to the different steady-state values of bond quantities between the two countries. The results in annualized percentage changes for the different calibrations are contained in Table 4 and Table 5.

Lastly, it is worth noting that when there are no frictions at all (ϕ_L=0), the two assets become perfect substitutes and a reduction in the supply of long-term bonds does not generate any effect on yields and on the macroeconomy, as agents can simply increase their holdings of short-term bonds by the same amount. In such a case, the identification of the *portfolio rebalancing* channel of large asset purchases would not be possible.

3.2.3 Sensitivity Analysis: Constrained vs Unconstrained Policy Rate

In order to simulate recent large asset purchases as realistic as possible, the baseline calibration outlined in paragraph 3.1 has imposed a constrained policy rate, i.e. the short-term interest rate is prevented from reacting to macro developments. An interesting exercise consists in comparing the cases when the policy rate is constrained and non-constrained. When the policy rate is allowed to follow a standard Taylor rule, the effects of large asset purchases on the variables of interest are expected to be smaller. In this case, the impact of large asset purchases is mitigated by the increase in the short-term rate due to the prescriptions of the Taylor rule. In effect, the impulse response functions displayed in Figure 11 and Figure 12 confirm this conjecture. Thus, the stimulus provided to the economy by the simulated asset purchases by the Fed and the BoE is significantly larger with a constrained policy rate (solid red line) than with a free policy rate (dashed black line). As stressed by Harrison (2012a), this provides a motivation for the implementation of large asset purchases by the central bank when the policy rate is constrained by the ZLB.[17]

[17] A similar argument is discussed in Christiano et al. (2011), who show that the government-spending multiplier can be much larger than one when the zero lower bound on the nominal interest rate binds.

4 Concluding Remarks

This paper has developed a DSGE model capable of evaluating some of the effects of large purchases of treasuries by central banks. The model exhibits imperfect asset substitutability and a feedback from the term structure to the macroeconomy, both generated through the introduction of portfolio adjustment frictions. As a result, the model is able to isolate a *portfolio rebalancing* channel of QE. Given the novelties introduced, the theoretical framework proposed in this paper is more consistent with reality than similar models in the literature (Chen et al., 2012; Harrison, 2012a,b). The model is employed to evaluate the effects of recent specific large asset purchase programs in the US and in the UK. More specifically, the focus has been on QE2 in the US (from November 2010 to June 2011 - around $800 billion of purchases), and the first phase of the APF operations in the UK (from March 2009 to January 2010 - around £200 billion of purchases). Both phases have been characterized exclusively by purchases of medium- and long-term government securities.

The simulation results of the calibrated model are realistic and generally consistent with those obtained in the literature using different techniques. However, the estimated macroeconomic effect in the US has been found to be slightly larger than in previous studies, while in the UK a bit smaller. Overall, the findings suggest that large asset purchases of government assets had substantial stimulating effects both in terms of lower long-term yields and higher output and inflation in both countries. These effects seem to be generally larger for the UK than for the US. This is not surprising, given that the size of asset purchases characterizing the phases of QE under consideration has been larger, in relative terms, in the UK rather than in the US. More specifically, my preferred model specification indicates that large asset purchases of QE2 in the US had a peak effect on long-term rates in annualized terms of around -63 basis points, on the level of real GDP of 0.92%, and on inflation of 0.37 percentage points. In the UK, the preferred model specification suggests that the first phase of the APF program had a peak effect on long-term rates of -69 basis points, on the level of real GDP of 1.25%, and on inflation of 0.49 percentage points. The empirical results are nonetheless subject to some uncertainty associated with the degree of substitutability among assets of different maturities, and, more importantly, with the speed of the exit strategy chosen by monetary authorities.

All in all, the most substantive contribution of this paper is to provide a new setting through which the effects of large purchases of treasuries by central banks can be evaluated within a microfounded macro framework with optimizing agents. This study points to further avenues for future research. First of all, through the estimation of the model it would be possible to check whether actual data support the theoretical framework. Moreover, the model can be easily extended in several directions, e.g. to include an explicit and more structured central bank's balance sheet, a wider term structure representation, or different types of assets, such as corporate bonds. Lastly, it would be worth combining this framework with those proposed by Cúrdia and Woodford (2010), Gertler and Kiyotaki (2010), Brendon et al. (2011), Del Negro et al. (2011) and Gertler and Karadi (2011), which, by introducing financial intermediaries, are able to isolate the *credit channel* of QE.

References

Adjemian, S., Bastani, H., Juillard, M., Mihoubi, F., Perendia, G., Ratto, M., and Villemot, S. (2011). Dynare: Reference manual, version 4. Dynare Working Papers 1, CEPREMAP.

Altig, D., Christiano, L. J., Eichenbaum, M., and Lind, J. (2011). Firm-specific capital, nominal rigidities and the business cycle. *Review of Economic Dynamics*, 14(2):225–247.

Andrés, J., López-Salido, J. D., and Nelson, E. (2004). Tobin's imperfect asset substitution in optimizing general equilibrium. *Journal of Money, Credit and Banking*, 36(4):665–690.

Bagus, P. (2010). Will there be QE3, QE4, QE5...? *leeconomics* blog, (December 31, 2010).

Baumeister, C. and Benati, L. (2013). Unconventional monetary policy and the Great Recession: Estimating the impact of a compression in the yield spread at the zero lower bound. *International Journal of Central Banking*, 9(2):165–212.

Bernanke, B. S. and Reinhart, V. R. (2004). Conducting monetary policy at very low short-term interest rates. *American Economic Review*, 94(2):85–90.

Blinder, A. S. (2010). Quantitative easing: Entrance and exit strategies. *Federal Reserve Bank of St. Louis Review*, Nov-Dec:465–480.

Board of Governors of the Federal Reserve System (2012). Press Release. September 13, 2012. http://www.federalreserve.gov/newsevents/press/monetary/20120913a.htm.

Borio, C. and Disyatat, P. (2010). Unconventional monetary policies: An appraisal. *The Manchester School*, 78:53–89.

Bowdler, C. and Radia, A. (2012). Unconventional monetary policy: The assessment. *Oxford Review of Economic Policy*, 28(4):603–621.

Brendon, C., Paustian, M., and Yates, T. (2011). Optimal conventional and unconventional monetary policy in the presence of collateral constraints and the zero bound. Unpublished manuscript.

Bridges, J. and Thomas, R. (2012). The impact of QE on the UK economy: Some supportive monetarist arithmetic. Bank of England working papers 442, Bank of England.

Caglar, E., Chadha, J. S., Meaning, J., Warren, J., and Waters, A. (2012). Non-conventional monetary policies: QE and the DSGE literature. In Chadha, J. and Holly, S., editors, *Interest Rates, Prices and Liquidity: Lessons from the Financial Crisis*, chapter 11.

Chadha, J. S. and Corrado, L. (2012). Macro-prudential policy on liquidity: What does a DSGE model tell us? *Journal of Economics and Business*, 64(1):37–62.

Chadha, J. S., Corrado, L., and Meaning, J. (2012). Reserves, liquidity and money: An assessment of balance sheet policies. CEIS Working Paper 230, CEIS.

Chen, H., Cúrdia, V., and Ferrero, A. (2012). The macroeconomic effects of large-scale asset purchase programmes. *Economic Journal*, 122(564):F289–F315.

Christensen, J. H. E. and Rudebusch, G. D. (2012). The response of interest rates to US and UK Quantitative Easing. *Economic Journal*, 122(564):F385–F414.

Christiano, L. J. and Eichenbaum, M. (1992). Current real-business-cycle theories and aggregate labor-market fluctuations. *American Economic Review*, 82(3):430–450.

Christiano, L. J., Eichenbaum, M., and Evans, C. L. (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, 119(1):1–45.

Christiano, L. J., Eichenbaum, M., and Rebelo, S. (2011). When is the government spending multiplier large? *Journal of Political Economy*, 119(1):78–121.

Chung, H., Laforte, J.-P., Reifschneider, D., and Williams, J. C. (2012). Have we underestimated the likelihood and severity of zero lower bound events? *Journal of Money, Credit and Banking*, 44:47–82.

Cúrdia, V. and Woodford, M. (2010). Conventional and unconventional monetary policy. *Federal reserve Bank of St. Louis Review*, (May):229–264.

D'Amico, S., English, W., López-Salido, D., and Nelson, E. (2012). The Federal Reserve's large-scale asset purchase programmes: Rationale and effects. *Economic Journal*, 122(564):F415–F446.

D'Amico, S. and King, T. B. (2013). Flow and stock effects of large-scale treasury purchases: Evidence on the importance of local supply. *Journal of Financial Economics*, 108(2):425–448.

Del Negro, M., Eggertsson, G., Ferrero, A., and Kiyotaki, N. (2011). The great escape? A quantitative evaluation of the Fed's liquidity facilities. Staff Reports 520, Federal Reserve Bank of New York.

Dib, A. (2010). Banks, credit market frictions, and business cycles. Bank of Canada Working Papers 10-24.

Dixit, A. K. and Stiglitz, J. E. (1977). Monopolistic competition and optimum product diversity. *American Economic Review*, 67(3):297–308.

Doh, T. (2010). The efficacy of large-scale asset purchases at the zero lower bound. *Federal Reserve Bank of Kansas City Economic Review*, (Q II):5–34.

Eggertsson, G. B. and Woodford, M. (2003). The zero bound on interest rates and optimal monetary policy. *Brookings Papers on Economic Activity*, 2003(1):139–211.

Falagiarda, M. (2012). Quantitative Easing: Origins, channels, and recent experiences. Unpublished manuscript.

Falagiarda, M. and Marzo, M. (2012). A DSGE model with endogenous term structure. Quaderni DSE Working Paper 830, Department of Economics, Università di Bologna.

Gagnon, J., Raskin, M., Remache, J., and Sack, B. (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking*, 7(1):3–43.

Gertler, M. and Karadi, P. (2011). A model of unconventional monetary policy. *Journal of Monetary Economics*, 58(1):17–34.

Gertler, M. L. and Kiyotaki, N. (2010). Financial intermediation and credit policy in business cycle analysis. In Friedman, B. M. and Woodford, M., editors, *Handbook of Monetary Economics*, volume 3, chapter 11, pages 547–599.

Glick, R. and Leduc, S. (2012). Central bank announcements of asset purchases and the impact on global financial and commodity markets. *Journal of International Money and Finance*, 31(8):2078–2101.

Hamilton, J. D. and Wu, J. C. (2012). The effectiveness of alternative monetary policy tools in a zero lower bound environment. *Journal of Money, Credit and Banking*, 44:3–46.

Harrison, R. (2012a). Asset purchase policies and portfolio balance effects: A DSGE analysis. In Chadha, J. and Holly, S., editors, *Interest Rates, Prices and Liquidity: Lessons from the Financial Crisis*, chapter 5.

Harrison, R. (2012b). Asset purchase policy at the effective lower bound for interest rates. Bank of England working papers 444, Bank of England.

Hilberg, B. and Hollmayr, J. (2011). Asset prices, collateral and unconventional monetary policy in a DSGE model. Working Paper Series 1373, European Central Bank.

Ireland, P. N. (2004). Money's role in the monetary business cycle. *Journal of Money, Credit and Banking*, 36(6):969–83.

Joyce, M. A. S., Lasaosa, A., Stevens, I., and Tong, M. (2011a). The financial market impact of quantitative easing in the United Kingdom. *International Journal of Central Banking*, 7(3):113–161.

Joyce, M. A. S., Miles, D., Scott, A., and Vayanos, D. (2012). Quantitative easing and unconventional monetary policy: An introduction. *Economic Journal*, 122(564):F271–F288.

Joyce, M. A. S. and Tong, M. (2012). QE and the gilt market: A disaggregated analysis. *Economic Journal*, 122(564):F348–F384.

Joyce, M. A. S., Tong, M., and Woods, R. (2011b). The United Kingdom's quantitative easing policy: Design, operation and impact. *Bank of England Quarterly Bulletin*, Q3:200–212.

Kapetanios, G., Mumtaz, H., Stevens, I., and Theodoridis, K. (2012). Assessing the economy-wide effects of quantitative easing. *Economic Journal*, 122(564):F316–F347.

Keynes, J. M. (1936). *The general theory of employment, interest, and money*. Macmillan, London.

Kim, J. (2000). Constructing and estimating a realistic optimizing model of monetary policy. *Journal of Monetary Economics*, 45(2):329–359.

Klyuev, V., de Imus, P., and Srinivasan, K. (2009). Unconventional choices for unconventional times: Credit and quantitative easing in advanced economies. IMF Staff Position Note SPN/09/27.

Kozicki, S., Santor, E., and Suchanek, L. (2012). Central bank balance sheets and long-term forward rates. In Chadha, J. and Holly, S., editors, *Interest Rates, Prices and Liquidity: Lessons from the Financial Crisis*, chapter 7.

Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). The effects of quantitative easing on interest rates: Channels and implications for policy. *Brookings Papers on Economic Activity*, (Fall):215–287.

Krugman, P. R. (1998). It's baaack: Japan's slump and the return of the liquidity trap. *Brookings Papers on Economic Activity*, 1998(2):137–205.

Leeper, E. M. (1991). Equilibria under active and passive monetary and fiscal policies. *Journal of Monetary Economics*, 27(1):129–147.

Ljungqvist, L. and Sargent, T. (2004). *Recursive macroeconomic theory*. MIT Press.

Marzo, M., Söderström, U., and Zagaglia, P. (2008). The term structure of interest rates and the monetary transmission mechanism. Unpublished manuscript.

Meaning, J. and Zhu, F. (2011). The impact of recent central bank asset purchase programmes. *BIS Quarterly Review*, December.

Meier, A. (2009). Panacea, curse, or nonevent? Unconventional monetary policy in the United Kingdom. IMF Working Papers 09/163, International Monetary Fund.

Neely, C. J. (2010). The large scale asset purchases had large international effects. Working Papers 2010-018, Federal Reserve Bank of St. Louis.

Orphanides, A. (2004). Monetary policy in deflation: The liquidity trap in history and practice. *The North American Journal of Economics and Finance*, 15(1):101–124.

Rotemberg, J. J. (1982). Monopolistic price adjustment and aggregate output. *Review of Economic Studies*, 49(4):517–531.

Schmitt-Grohé, S. and Uribe, M. (2004). Optimal fiscal and monetary policy under imperfect competition. *Journal of Macroeconomics*, 26(2):183–209.

Schmitt-Grohé, S. and Uribe, M. (2007). Optimal simple and implementable monetary and fiscal rules. *Journal of Monetary Economics*, 54(6):1702–1725.

Smets, F. and Wouters, R. (2007). Shocks and frictions in us business cycles: A Bayesian DSGE approach. *American Economic Review*, 97(3):586–606.

Stroebel, J. C. and Taylor, J. B. (2012). Estimated impact of the Fed's mortgage-backed securities purchase program. *International Journal of Central Banking*, 8(2):1–42.

Svensson, L. E. O. (2003). Escaping from a liquidity trap and deflation: The foolproof way and others. *Journal of Economic Perspectives*, 17(4):145–166.

Swanson, E. T. (2011). Let's twist again: A high-frequency event-study analysis of Operation Twist and its implications for QE2. *Brookings Papers on Economic Activity*, 42(1):151–207.

Taylor, J. B. (1993). Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39:195–214.

Tobin, J. (1969). A general equilibrium approach to monetary theory. *Journal of Money, Credit and Banking*, 1(1):15–29.

Tobin, J. (1982). Money and finance in the macroeconomic process. *Journal of Money, Credit and Banking*, 14(2):171–204.

Vayanos, D. and Vila, J.-L. (2009). A preferred-habitat model of the term structure of interest rates. Working Paper 15487, National Bureau of Economic Research.

Wright, J. H. (2012). What does monetary policy do to long-term interest rates at the zero lower bound? *Economic Journal*, 122(564):F447–F466.

Zagaglia, P. (2013). Forecasting long-term interest rates with a general-equilibrium model of the euro area: What role for liquidity services of bonds? *Asia-Pacific Financial Markets*, pages 1–48.

Tables and Figures

Table 1: Steady-state values of some variables

Notation	Description	SS value
Y	Output	1 (norm.)
C	Consumption-output ratio	0.57
I	Investment-output ratio	0.23
T/Y	Taxes-output ratio	0.1972
$L/(1-L)$	Ratio of market to non-market activities	0.3
R	Gross money-market rate	1.010

Table 2: Benchmark calibration of some parameters

Notation	Description	Benchmark value
	Preferences and technology	
α	Share of capital in the production function	0.36
β	Intertemporal discount factor	0.994
σ	Elasticity of intertemporal substitution	0.5
χ	Elasticity of money demand	7
ψ	Elasticity of labor supply	1
γ	Habit formation	0.7
θ	Elasticity of substitution between varieties of goods	6
ϕ_P	Price adjustment costs	100
	Fiscal and monetary policy	
ψ_1	Fiscal policy response to short-term debt	0.3
ψ_2	Fiscal policy response to long-term debt	0.3
α_π	Monetary policy response to inflation	1.5
α_Y	Monetary policy response to output	0
α_R	Monetary policy inertia	0.997
	Autoregressive parameters	
ϕ_A	Technology shock	0.95
ϕ_G	Government spending shock	0.90
ϕ_{BL}	LT bonds shock	0.90
	Standard deviations	
σ_A	Technology shock	0.01
σ_G	Government spending shock	0.012
σ_R	Monetary policy shock	0.005
σ_{BL}	LT bonds shock	0.01

Table 3: Calibration values of the key parameters and steady-states

Notation	Description	US	UK
ϕ_L	Portfolio adjustment frictions	0.01	0.01
$B + B_L$	Total debt on GDP	0.496	0.542
B	Total ST debt on total debt	0.188	0.052
B_L	Total LT debt on total debt	0.308	0.490
B_L^H	LT debt held by households	0.250	0.479
B_L^{CB}	LT debt held by the CB	0.058	0.011
σ_x	Magnitude of the asset purchases	1	12
ϕ_x	Persistence of the asset purchases	0.83[1]	0.83[1]
	Approximated duration of the shock	3Q	4Q

Notes: [1]A persistence of 0.83 reflects an exit strategy of approximately 6 years.
Sources: The values are calculated by combining data from the OECD statistical database, the Federal Reserve Statistical Release, the Bank of England Statistical Interactive Database, and the Bank of England APF Gilt Operational Results Dataset. Notice that they represent only approximations, given the difficulties of combining data with different frequency.

Table 4: Estimated effect of the LSAP2 on the LT rate,[1] output and inflation (US - annualized)

Study	Method	Total impact on LT Rate	Peak impact on Output	Peak impact on Inflation
KVJ (2011)[2]	Event study/regressions	-33 bp	-	-
D'Amico et al. (2012)	Regressions	-55 bp	-	-
Chen et al. (2012)	DSGE model	-30 bp[3]	0.4%	0.05%
Chung et al. (2012)	FRB/US model	-20 bp[3]	0.6%	0.1%
My calibrated model	Specification			
	Baseline	**-63 bp**	**0.92%**	**0.37%**
	High persistence ($\phi_x = 0.88$)	-61 bp	1.27%	0.59%
	Low persistence ($\phi_x = 0.76$)	-65 bp	0.66%	0.23%
	Higher frictions ($\phi_L = 0.02$)	-77 bp	1.57%	0.75%
	Lower frictions ($\phi_L = 0.005$)	-46 bp	0.50%	0.17%

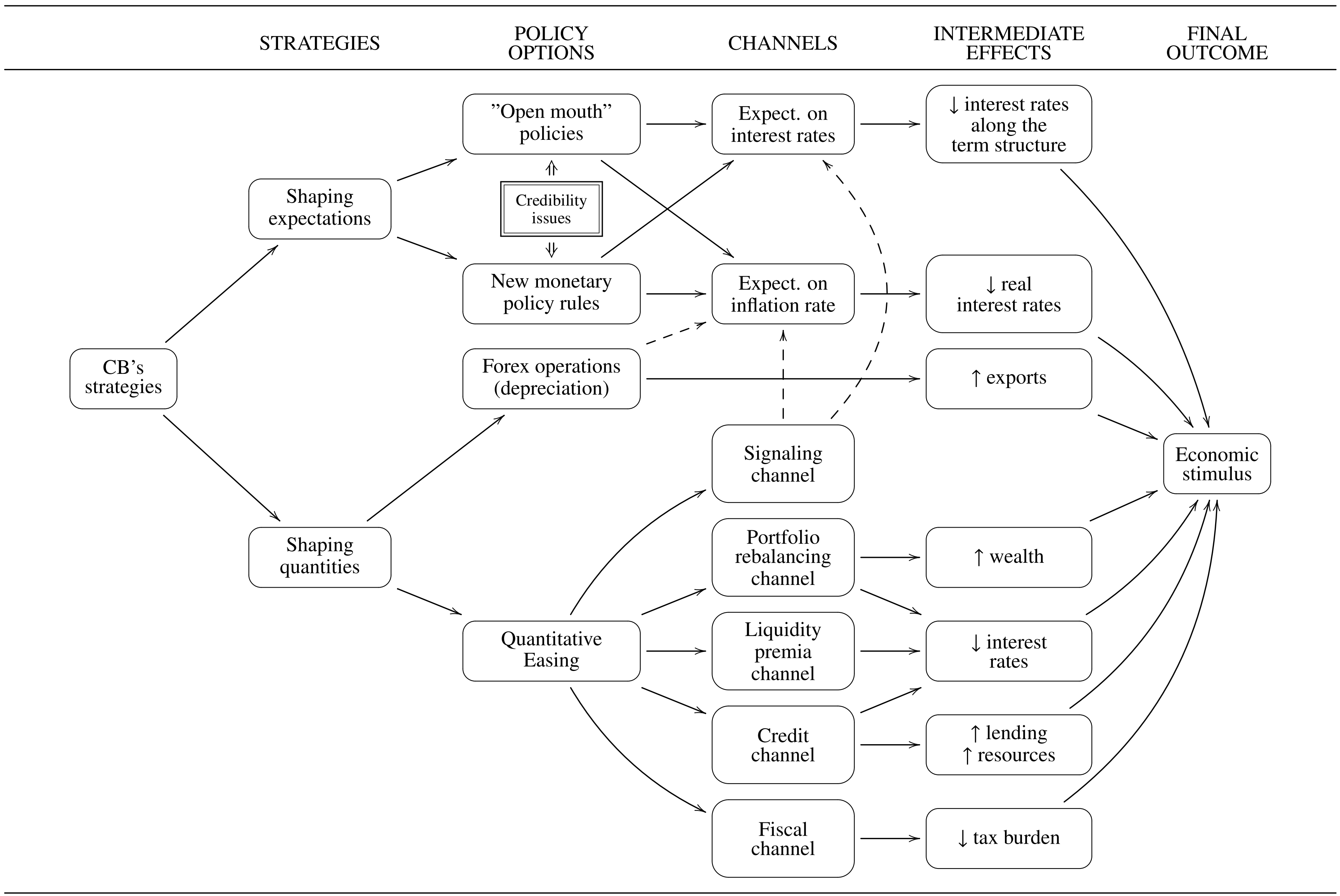
Notes: [1]10-year Treasury yield. [2]Krishnamurthy and Vissing-Jorgensen (2011). [3]Effect on the risk premium.

Table 5: Estimated effect of the first phase of the APF on the LT rate,[1] output and inflation (UK - annualized)

Study	Method	Total impact on LT Rate	Peak impact on Output	Peak impact on Inflation
Glick and Leduc (2012)	Event study	-49 bp	-	-
Harrison (2012a)	DSGE model	-60 bp[2]	1.3%	0.13%
Joyce et al. (2011a)	Event study	-125 bp	-	-
Joyce et al. (2011b)	SVAR	-	1.5%	0.75%
Joyce et al. (2011b)	Reduced form model	-	1.5-2.5%	0.75-2.25%
Kapetanios et al. (2012)	Time-series model	-	1.5%	1.25%
Bridges and Thomas (2012)	Time-series model	-	2%	1%
My calibrated model	Specification			
	Baseline	**-69 bp**	**1.25%**	**0.49%**
	High persistence ($\phi_x = 0.88$)	-66 bp	1.61%	0.73%
	Low persistence ($\phi_x = 0.76$)	-71 bp	0.94%	0.30%
	Higher frictions ($\phi_L = 0.02$)	-69 bp	1.31%	0.53%
	Lower frictions ($\phi_L = 0.005$)	-68 bp	1.13%	0.41%

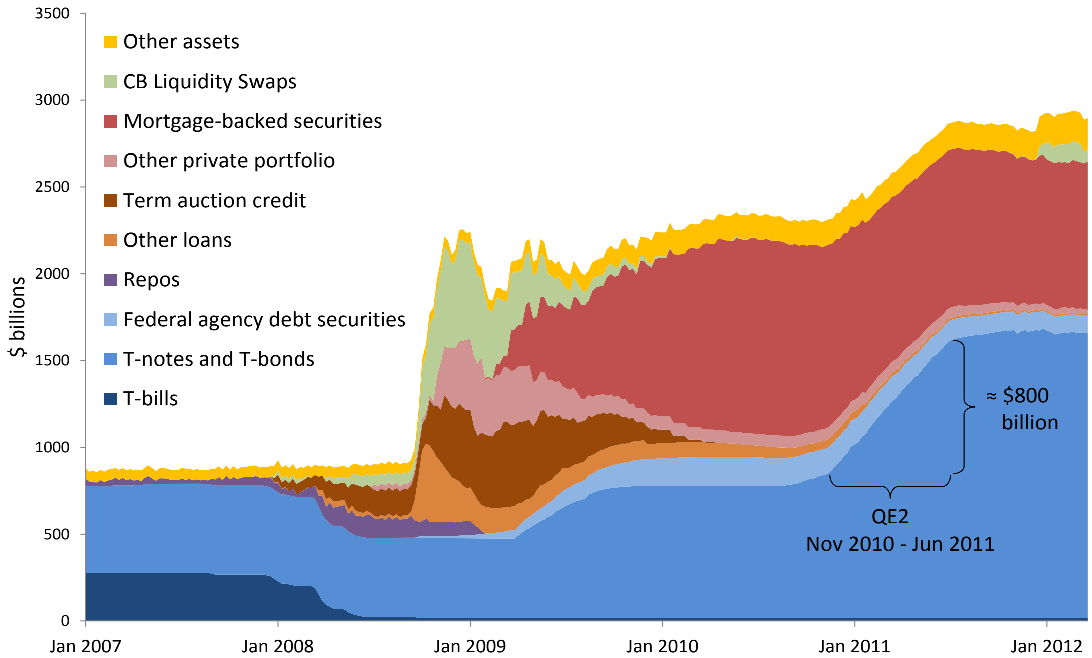
Notes: [1]10-year Treasury yield. [2] 5-year rate.

Figure 1: Facing the ZLB: Strategies, policy options and channels



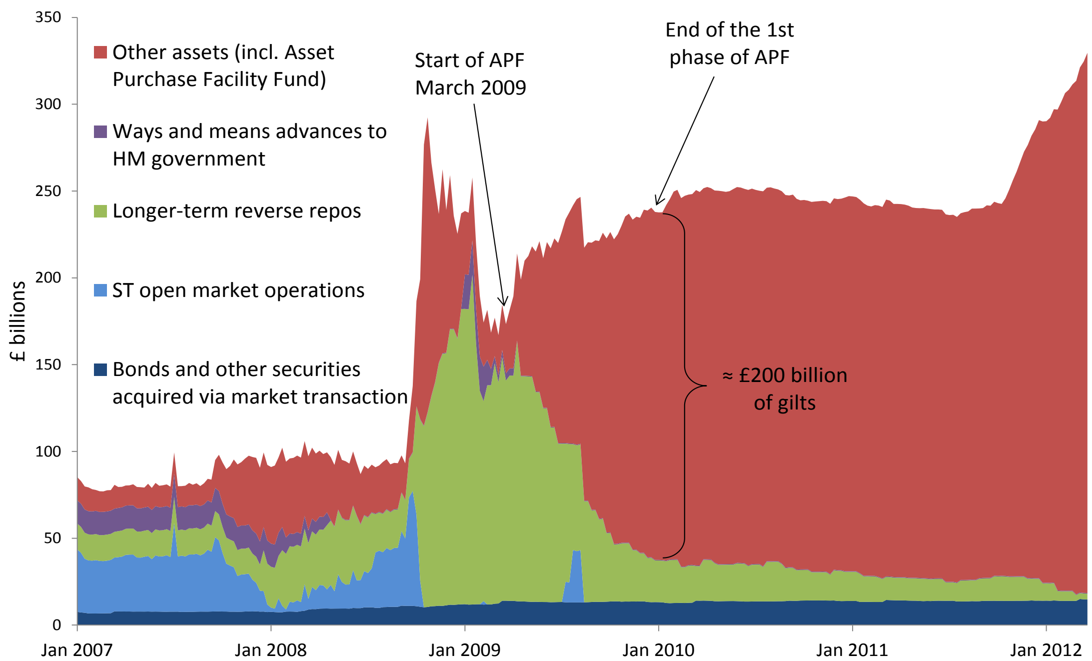
Source: Falagiarda (2012).

Figure 2: Evolution of Fed assets composition



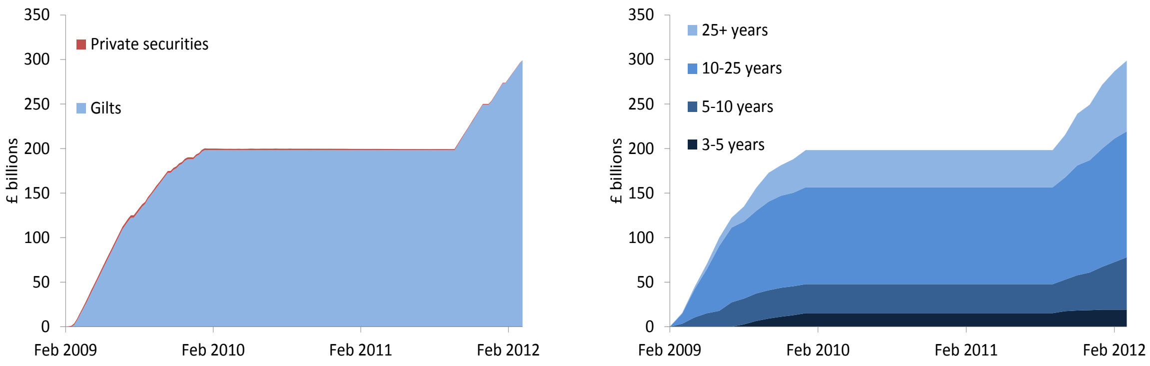
Source: Author's elaboration on data from the Federal Reserve Statistical Release.

Figure 3: Evolution of BoE assets composition



Source: Author's elaboration on data from the Bank of England Statistical Interactive Database.

Figure 4: Cumulative BoE asset purchases by type (a) and cumulative gilts purchases by maturity (b)



(a) (b)

Source: Author's elaboration on data from the Bank of England Statistical Interactive Database.

Figure 5: Impulse responses to the simulated Fed's asset purchase shock

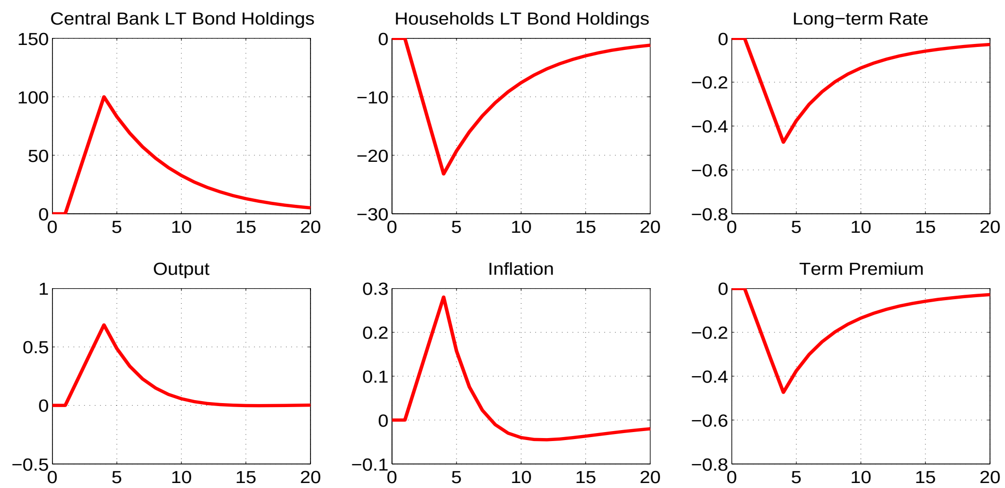


Figure 6: Impulse responses to the simulated BoE's asset purchase shock

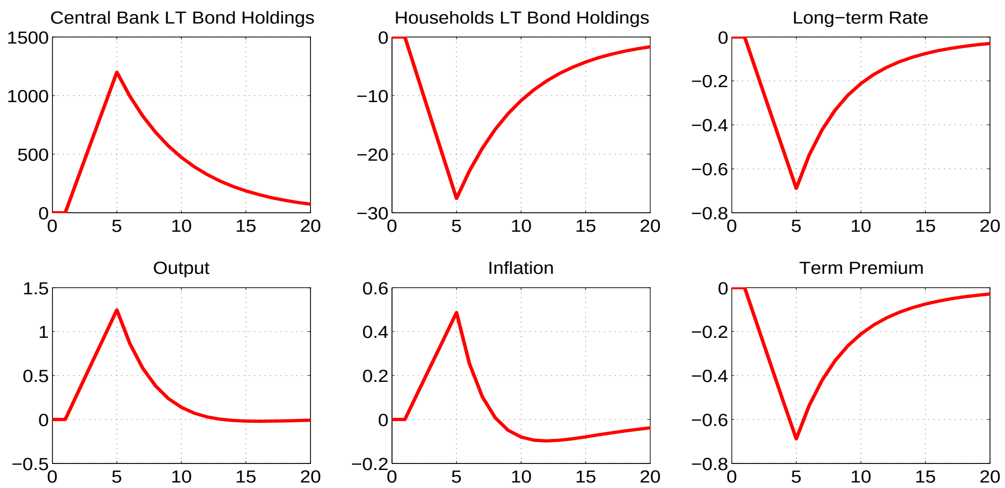


Figure 7: Impulse responses to the simulated Fed's asset purchase shock when varying the persistence of the shock

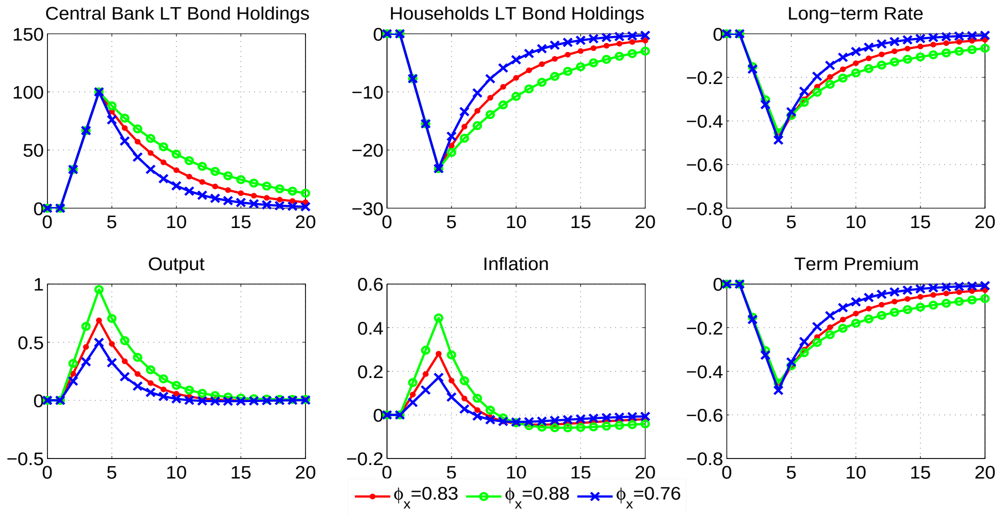


Figure 8: Impulse responses to the simulated BoE's asset purchase shock when varying the persistence of the shock

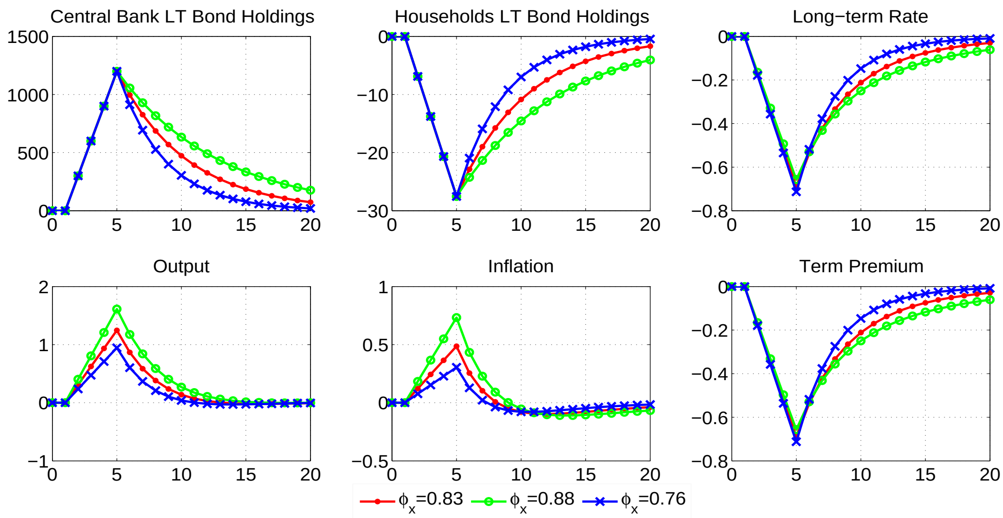


Figure 9: Impulse responses to the simulated Fed's asset purchase shock when varying bond transaction costs

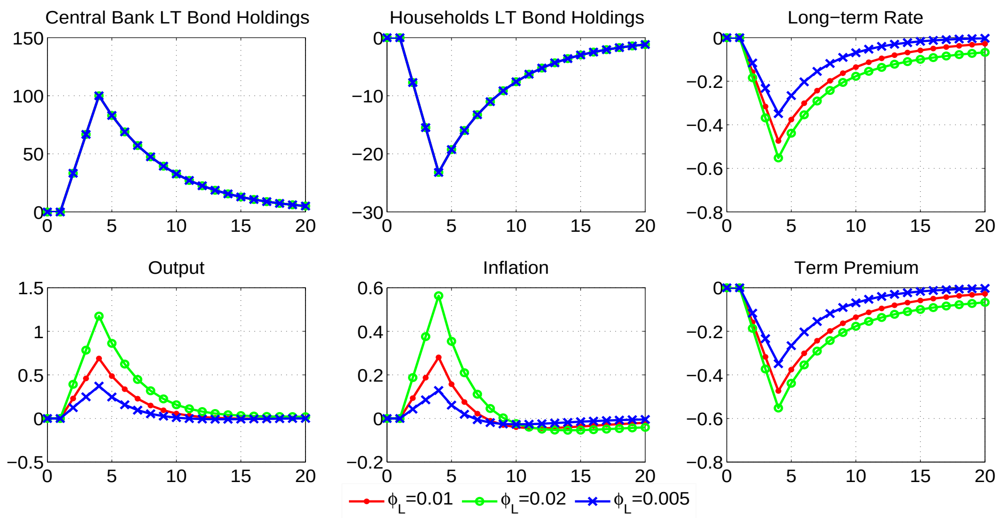


Figure 10: Impulse responses to the simulated BoE's asset purchase shock when varying bond transaction costs

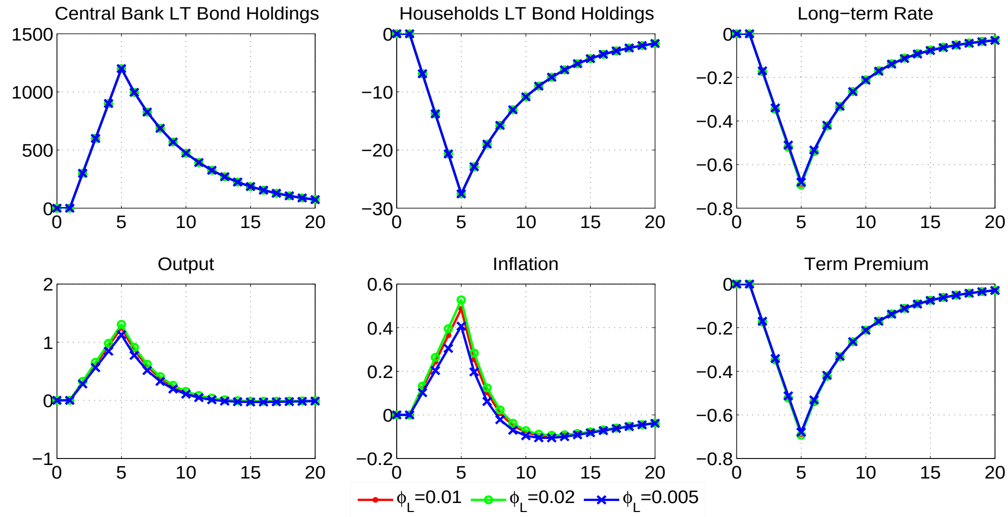


Figure 11: Impulse responses to the simulated Fed's asset purchase shock: constrained vs unconstrained ST rate

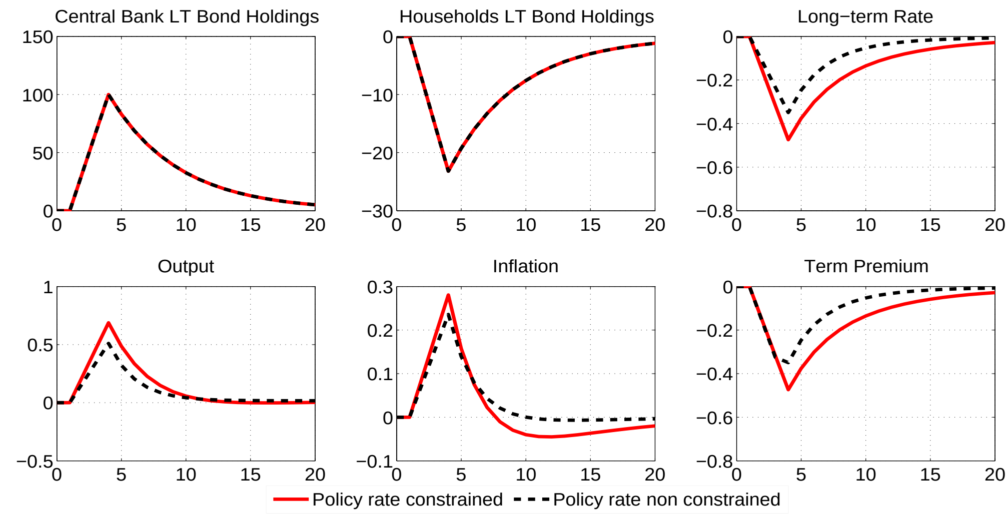
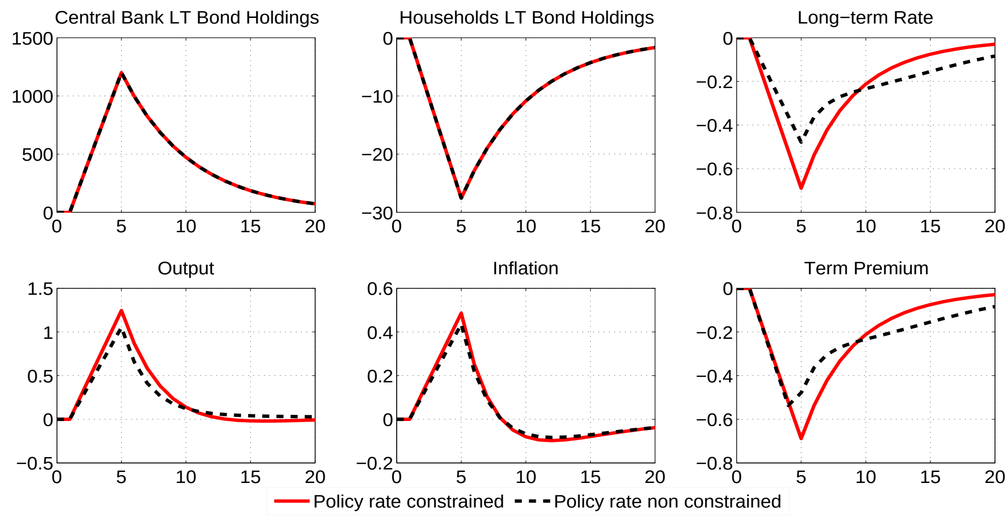


Figure 12: Impulse responses to the simulated BoE's asset purchase shock: constrained vs unconstrained ST rate



Announcements of ECB Unconventional Programs: Implications for the Sovereign Risk of Italy

Matteo Falagiarda* Stefan Reitz†

First version: August 2013
This version: February 2014‡

Abstract

This paper studies the effects of ECB communications about unconventional monetary policy operations on the perceived sovereign risk of Italy over the last five years. More than fifty events concerning non-standard operations are identified and classified with respect to the specific ECB program. The empirical results are derived from both an event-study analysis and a GARCH framework, which uses Italian long-term bond futures to disentangle expected from unexpected policy actions. We find that the ECB announcements about unconventional monetary policies substantially reduced Italian long-term government bond yield spread relative to German counterparts. Particularly, among the different types of measures, news about the *Securities Markets Programme* and the *Outright Monetary Transactions* are found to be effective in affecting the perceived sovereign risk of Italy.

KEYWORDS: central bank communications, unconventional monetary policy, European sovereign debt crisis, event-study, GARCH models

JEL Classification: E43, E52, E58, G01, G12

*Department of Economics, University of Bologna. Mail: matteo.falagiarda2@unibo.it Address: Piazza Scaravilli 2 - 40126 Bologna (Italy). Office Phone: +39 051 2092641

†Institute for Quantitative Business and Economics Research, University of Kiel, and Kiel Institute for the World Economy.

‡We benefited from the suggestions of Maria Grazia Attinasi, Jacopo Cimadomo, Tobias Dieler, Andrea Fracasso, Harmen Lehment, Michele Lenza, Nikola Mirkov, Umberto Muratori, Riccardo Rovelli and Alessandro Saia. We thank participants at seminars at the European Central Bank, the Deutsche Bundesbank, the University of Bologna and the Kiel Institute for the World Economy. We are also grateful to participants at the conference *Walk the talk? Challenges for monetary policy actions and communication in uncertain times* organized by the Viessman European Research Center (Waterloo, Ontario), and at the *IWH Workshop on Central Bank Communication and Decision Making* (Halle, Germany). The usual disclaimer applies.

1 Introduction

As the recent financial crisis unfolded international investors became increasingly concerned with the sustainability of government debt in a number of European countries. Long-term government bond spreads relative to Germany have increased dramatically for most euro area countries. In particular, during the period 2008-2010 the Italian spread vis-á-vis Germany widened to almost 200 basis points from about 30 basis points, the average level after the introduction of the euro in 1999. Since the mid-2011, the Italian long-term government bond yield differential has widened even more markedly reaching peaks of over 550 basis points in the late months of 2011 in connection with the Italian political crisis. Only at the end of 2012 the surge in the spread calmed down approaching the 300 basis point level.

This unprecedented increase in euro area sovereign bond yield spreads reflects, *inter alia*, growing concerns in financial markets about governments' capacity to satisfy their future debt obligations. In fact, an increasing spread indicates a significant risk premium that investors demand when lending to a specific government, which, in turn, suffers the higher cost of borrowing and a limited capacity to access capital markets. There is strong empirical evidence that countries borrowing excessively, i.e. with a high debt-to-GDP ratio and/or with substantial fiscal deficits, are likely to face financial markets asking for higher default premia (Goldstein and Woglom, 1991; Bayoumi et al., 1995; Schuknecht et al., 2009). This market-based mechanism of fiscal discipline seems to have been switched off until the first half of 2008, when bond yields of Italian government debt - and, more generally, of a number of other euro area countries - were relatively close to the German ones (Figure 1).

[Figure 1 about here]

The reassessment and differentiation of country risk by financial markets can also be observed by looking at the pattern of the Italian sovereign credit default swaps (CDS) premia (Figure 2). The time series evolves very similar to the Italian bond yield spread over the last five years with a first substantial increase in the late 2008 and a dramatic hike starting from the mid of 2011. Recent contributions in the empirical literature (Attinasi et al., 2011; Gerlach et al., 2010; Arghyrou and Kontonikas, 2012; De Santis, 2012; Giordano et al., 2013) have found that the widening of euro countries' sovereign bond spreads relative to the German Bund observed during the recent crisis is due both to countries' fiscal positions and/or macroeconomic fundamentals, and to more general factors such as liquidity risk, international risk aversion or contagion effects.

[Figure 2 about here]

Besides facing serious sovereign debt tensions, the euro area was earlier also severely stressed by the breakdown of financial and interbank markets following Lehman Brothers' collapse in 2008. To stop the meltdown of the financial system, governments, international and European institutions proposed unprecedented unconventional measures, such as bank-rescue packages, bailout agreements, and financial-support schemes. When it comes to monetary policy the European Central Bank (ECB) as well as the Federal Reserve and the Bank of England reduced their key interest rates to historically low levels (Figure 3). In fact, the zero-lower bound (ZLB) of interest rates quickly became a serious concern for monetary policy as conventional monetary policy measures consisting of standard open market operations were unable to restore the functioning of interbank markets. While the monetary authorities in the US and the UK intervened by implementing unprecedented non-sterilized interventions often referred to as *Quantitative Easing* (QE),[1] the ECB adopted a less aggressive strategy by launching a number of *temporary* non-standard measures and programs to face liquidity and sovereign debt problems. As a result of non-standard monetary policies, the asset side of the balance sheet of the Federal Reserve and the Bank of England almost tripled in the last five years, whereas that of the ECB almost doubled.

[Figure 3 about here]

While the effectiveness of unconventional monetary programs in the US and the UK has been extensively analyzed,[2] the evidence on the unconventional measures adopted by the ECB is scarce. Existing contributions to the literature focused on the core variables of monetary policy and investigated the effect of specific ECB unconventional policies on interbank rates (Abbassi and Linzert, 2011), on covered bond markets (Beirne et al., 2011), on money market rates (Angelini et al., 2011), on some monetary and credit variables (Giannone et al., 2011), on bank credit volumes (Peersman, 2011), and on macroeconomic variables (Lenza et al., 2010). Currently, however, there have been no studies on the impact of ECB unconventional monetary measures on the perceived sovereign risk of euro area countries. In fact, important spillover effects from monetary to fiscal policy may arise as extensive liquidity provision may reduce the risk of government bailouts thereby decreasing expected future debt-to-GDP ratios. As stressed by Gerlach et al. (2010) and Arghyrou and Kontonikas (2012), the role of domestic banking sectors is crucial, with the financial system transforming global risk into sovereign risk through two channels. First, in periods of financial stress banks should be recapitalized by governments, increasing its fiscal liabilities. Second, poor banking liquidity limits lending flows to private agents, exacerbating the recession and raising fiscal imbalances. The supporting spillover effect provides a strong incentive for governments to demand a continuation of unconventional monetary policy measures. This clearly contrasts with the central bank's ultimate goals, if the exit from non-standard measures is significantly postponed. To what extent these spillover effects establish a policy trade-off is an empirical question.[3]

The paper aims at filling this gap by empirically investigating whether and to what extent the unconventional monetary operations conducted by the ECB affected the Italian sovereign risk premium. Focusing on the period between 2008 and 2012, we assess the effect of ECB communications about unconventional monetary policies on the Italian spread vis-á-vis Germany.[4] More than fifty events (press conferences, press releases and speeches) concerning non-standard monetary operations are identified and classified with respect to the relevant ECB program. A

[1] QE policies are discussed in several studies (Krugman, 1998; Svensson, 2003; Bernanke and Reinhart, 2004; Orphanides, 2004; Borio and Disyatat, 2010; Joyce et al., 2012). These measures include purchases of treasuries, private securities, direct loans to banks, households and companies, and extensions of existing lending facilities.

[2] See, for example, Klyuev et al. (2009), Meier (2009), Baumeister and Benati (2010), Blinder (2010), Doh (2010), Neely (2010), Gagnon et al. (2011), Joyce et al. (2011b), Kozicki et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), Meaning and Zhu (2011), Swanson (2011), Bridges and Thomas (2012), Chen et al. (2012), Christensen and Rudebusch (2012), D'Amico et al. (2012), Glick and Leduc (2012), Hamilton and Wu (2012), Joyce and Tong (2012), Kapetanios et al. (2012), Wright (2012), and Falagiarda (2013).

[3] In a sense, our work tries to open the *black box* of the transmission of extraordinary interventions.

[4] For a survey on the theory and evidence of central bank communications, see Blinder et al. (2008).

comprehensive event-study analysis is conducted to observe the patterns of the Italian spread within a narrow time interval around each ECB announcement. As a robustness check, GARCH models are implemented to control for other factors than ECB communications affecting spread movements, such as disruption in financial markets, credit risk developments, and the business climate. Following Wright (2012), we isolate the surprise component of each central bank announcement by using the futures of Italian long-term bonds.

The results suggest that ECB communications about unconventional monetary policy measures substantially decreased the perceived sovereign risk of Italy. Particularly, the events occurring during the period 2010-2012 were more effective in reducing the Italian spread vis-á-vis Germany compared to events that took place at the onset of the crisis in 2008-2009. Not surprisingly, among the different types of unconventional operations, those introduced specifically to tackle sovereign debt tensions are found to be particularly effective in diminishing the Italian spread. These findings are important to guide monetary and fiscal policy in designing and implementing future unconventional programs.

The remainder of the paper proceeds as follows. Section 2 briefly presents the main non-standard measures recently implemented by the ECB. In Section 3, we discuss the main channels through which unconventional operations may affect financial markets and the economy. Section 4 and Section 5 report the empirical results from the event-study and the econometric analysis, respectively. Section 6 concludes.

2 ECB Unconventional Monetary Policies during the Crisis

In the aftermath of the financial crisis of 2007-2008, the ECB took a number of temporary non-standard measures aimed mainly at restoring a proper functioning of interbank markets. In fact, interbank markets were severely stressed due to solvency concerns, a consequent widespread lack of confidence, and liquidity hoarding of market participants. Financial markets suffered from substantial drawdowns as investors cut their exposures, with massive consequences for the real sector of the economy. During this stage, ECB unconventional measures included:[5] a) unlimited provision of liquidity through "fixed rate tenders with full allotment", allowing banks to get unlimited access to central bank liquidity at the main refinancing rate, subject to appropriate collateral; b) extension of the list of eligible collateral assets for refinancing operations; c) extension of the maturity of long-term refinancing operations, in order to reduce uncertainty and improve liquidity conditions for banks; d) liquidity provision in foreign currencies through swap lines with other central banks, in order to enhance banks' foreign currency funding.

A comprehensive package of non-standard measures was adopted by the ECB in May 2009, the *Enhanced Credit Support* (ECS), which reorganized the set of measures previously implemented and added to them. The five pillars characterizing the ECS included the four types of operations listed above plus a program of outright purchases of covered bonds, the so-called *Covered Bond Purchase Programme* (CBPP1). A further program of this kind was announced in November 2011 (CBPP2). The goal of the two programs was to rekindle the functioning of the covered bond market, constituting an essential source of banks' refinancing. Figure 4 displays the amount of bonds purchased by the ECB under CBPP1 and CBPP2 over time.

[5] For more details, see de Haan et al. (2012).

Under CBPP1, the ECB purchased euro-denominated covered bonds at a value of €60 billion over the period between May 2009 and June 2010. The purchases of CBPP2 were conducted between November 2011 and October 2012. The total amount of bonds acquired under CBPP2 was substantially smaller than under CBPP1.

A program specially designed to address sovereign-debt tensions was introduced by the ECB in May 2010. The so-called *Securities Market Programme* (SMP) involved purchases of euro area government bonds in the secondary markets, in order to ensure depth and liquidity in those market segments that were dysfunctional. The impact of these interventions was sterilized through specific operations to reabsorb the injected liquidity. Some details on the securities acquired under the SMP have been released in February 2013 and are reported in Table 1.

[Table 1 about here]

Approximately one half of the securities purchased by the ECB are Italian government bonds with an average remaining maturity of 4.5 years. The timing of SMP purchases is depicted in Figure 4, which shows that SMP operations have been carried out in two big waves, one in the first half of 2010 and the other in the second half of 2011.

A further program aimed at responding to the turbulences surrounding the European sovereign-debt crisis has been proposed in July 2012 and adopted in September 2012. According to this program, labeled *Outright Monetary Transactions* (OMT), once a government asks for financial assistance, the ECB can purchase government-issued bonds maturing in 1 to 3 years, provided that the bond-issuing country agrees to specific domestic measures (the so-called *conditionality* principle). The declared objective of the program is to safeguard "an appropriate monetary policy transmission and the singleness of the monetary policy" by lowering bond yields, especially at the long end of the yield curve, and thus reducing borrowing costs for countries and providing confidence to investors in the sovereign-bond markets. Also in this case, the liquidity created through the OMT is fully sterilized. Notice that, at the end of 2012, no OMT purchases were carried out yet. Thus, it can be argued that so far OMT was communication without intervention, in contrast with SMP that, being little transparent, was intervention without communication.

To gauge the effectiveness of different ECB unconventional operations, we classify them into seven categories:

- Liquidity provisions in foreign currencies through swap lines with other central banks (FOR).
- Unlimited provisions of liquidity through fixed rate tenders with full allotment for the main refinancing operations (FRTFA).
- Extensions of the list of collateral assets (COLL).
- Operations concerning long-term refinancing operations, such as extension of the maturity, new special long-term refinancing operations, and introduction of fixed rate tenders with full allotment (LTRO).
- Outright purchases of covered bonds (CBPP).
- Purchases of government bonds carried out under the Securities Market Programme (SMP).

- Purchases of government bonds carried out under the Outright Monetary Transactions (OMT).

This classification is used throughout the empirical part of the paper, where the effects of ECB non-standard operations are investigated. As long as financial markets are informationally efficient, the effect of monetary policies on asset prices occurs via changes of market expectations, typically at times when they are disclosed to market participants. We use the term announcement (or event) to refer to any means by which an unconventional policy decision was communicated to financial markets by the ECB, including press conferences, press releases and speeches. Table 2 reports all the events identified related to unconventional operations over the period 2008-2012. For each event we report the day and the exact time when it was announced, the type of the announcement, the nature of the measure announced, and a brief description.

[Table 2 about here]

3 The Channels of Unconventional Monetary Policies

In the literature, a number of different channels are reported through which ECB announcements may have affected the Italian spread. However, we decided to abstain from restricting the empirical model, which would imply a test of a specific transmission channel. Instead, we opt for a more general framework attempting to quantify the overall impact of ECB policy news regarding unconventional measures in the last five years. Nevertheless, in this section we briefly review the transmission mechanisms of unconventional monetary policies. First of all, unconventional monetary policies may affect asset prices and the real economy via the *signaling channel* emphasizing the role of expectations of private agents. In particular, central bank announcements are likely to exert their effects on financial markets through their influence on agents' expectations of future economic conditions and policy actions.

Another important channel of unconventional monetary policies is the so called *portfolio rebalancing channel* according to which purchases carried out by a central bank imply a rebalancing of investors' portfolios.[6] A necessary condition is the imperfect substitutability among different assets, i.e. assets are not perceived as perfect substitutes by investors.[7] By purchasing a particular security, the monetary authority reduces the amount of that security held by private agents usually in exchange of risk-free reserves. As a result, the asset price increases and the interest rate falls, creating more favorable conditions for economic recovery through the traditional monetary transmission mechanisms.[8]

Unconventional measures may then influence the economic system through the *liquidity premia channel*, also labeled *market functioning channel*. In a crisis like the one occurred after

[6]The portfolio balance approach was first described by Tobin (1958).

[7]Imperfect substitutability may emerge when agents are risk-averse and different assets have different risk characteristics, or when investors have "preferred habitats" (Vayanos and Vila, 2009).

[8]The reduction in yields is driven by a reduction of the risk premium, which may consist of different components. For instance, if the central bank purchases long-term government securities, it removes assets with high maturity from the market, i.e. high duration risk. Thus, less duration risk leads the market to require a lower term premium to bear that risk (Gagnon et al., 2011). A central bank engaging in purchases of private assets is also able to affect the premium associated with credit and liquidity risk. Whatever the effect at work, the likely outcome is a decrease in interest rates. A detailed analysis of all the determinants of the portfolio rebalancing channel is contained in Krishnamurthy and Vissing-Jorgensen (2011).

the demise of Lehman Brothers, markets are characterized by poor liquidity and, therefore, high liquidity risk premia on specific assets. The presence of a central bank acting as a protagonist in the markets could substantially improve market functioning and reduce liquidity risk premia. This new role of the central bank may make investors more prone to behave actively in the markets, knowing that they may sell assets to the monetary authority if necessary.

Non-standard monetary measures consisting of asset purchases, special loans, and extension of existing lending facilities are mostly financed by the creation of new central bank's reserves. Therefore, commercial banks experience an increase in their reserve balances at the central bank. This could promote an expansion of lending opportunities by banks. Through this *credit channel*, or *bank lending channel*, banks may provide more loans to households and companies, fostering consumption and investment spending.

How do ECB non-standard measures fit into this classification? All the types of unconventional operations implemented by the ECB may potentially signal future intentions and future economic developments (*signaling channel*), improve overall market functioning (*liquidity premia channel*) and work through the *credit channel*. However, only purchases of securities (CBPP, SMP, OMT) are able to affect financial markets and the economy through the *portfolio rebalancing channel*, which has been found to be one of the most important channels of unconventional monetary policies in the US and in the UK (Gagnon et al., 2011; Joyce et al., 2011a). Therefore, we might expect these latter programs to exert a larger impact on the Italian spread vis-á-vis Germany than the other ones, as they may affect asset prices via a wider set of transmission channels. This conjecture is strengthened by the fact that the SMP and OMT have been introduced with the declared objective to fight the sovereign debt tensions of the euro area. As a result, the signaling and liquidity effects might be amplified in comparison with other kinds of non-standard operations.

Beyond these traditional transmission channels, the ECB unconventional measures aimed at improving the functioning of interbank markets (FOR, FRTFA, COLL, LTRO, CBPP) may influence government bond spreads via banks' balance sheets. As stressed by Arghyrou and Kontonikas (2012), the role of domestic banking sectors is crucial, with the financial system transforming global risk into sovereign risk through two channels. First, in periods of financial stress banks should be recapitalized by governments, increasing its fiscal liabilities. Second, poor banking liquidity limits lending flows to private agents, exacerbating the recession and raising fiscal imbalances. Gerlach et al. (2010) show that during the height of the current crisis, up to almost one percentage point of euro area sovereign spreads can be explained by these banking related factors. Thus, the effect of unconventional operations designed to improve the health of interbank markets may help reduce the sovereign risk of a country.

4 An Event-Study Analysis

In this section, we perform an event-study analysis of ECB communications of unconventional monetary policy operations. In particular, we adopt a strategy similar to those recently used in Neely (2010), Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011) and Glick and Leduc (2012) to study the effect of non-standard measures implemented by the Federal Reserve. More specifically, we focus on changes in the Italian spread around ECB communications concerning non-standard monetary policy measures. Inspired by Craine and Martin (2008), we first report in Table 3 the standard deviations of daily spread changes (in basis points) for event and non-event days over the entire period 2008-2012 as well as over each individual year. Since more than half of our events occurred on Thursdays, we also calculate the standard deviation of daily spread changes for non-event Thursdays and non-event Governing Council meeting days (usually Thursdays).

[Table 3 about here]

As for the entire sample period, the figures show that the standard deviation of spread changes on event days is more than twice that on non-event days and Thurdays, and is still substantially larger than that on non-event Governing Council meeting days, stressing the importance of ECB announcements of unconventional measures on spread movements. Moreover, the volatility of spread changes has generally increased over time for event days, non-event days and non-event Thursdays. Lastly, the difference in volatility between event and non-event days in 2008 and 2009 was less pronounced than in the subsequent years suggesting that ECB communications of unconventional operations had a higher impact on the spread in 2010-2012 than in 2008-2009.

The third column of Table 4 presents daily changes in the Italian spread on each ECB announcement day, as well as the cumulative and average effect over all announcements. Moreover, it shows the cumulative and average effect when distinguishing events by year and type of the operation. The cumulative spread changes are considered as a measure for the overall effects. Basis points spread changes are measured using a one-day window, and are calculated as the difference between the closing spread value on the event day and the closing spread value on the day before. Moreover, we also report pseudo p-values defined as the proportion of daily changes during the period 2008-2012 that are larger in absolute value than the actual change on the announcement day (Neely, 2010; Glick and Leduc, 2012).

[Table 4 about here]

The figures reported in the third column of Table 4 indicate that the cumulative effect of ECB announcements on the Italian spread was a reduction of around 200 basis points, which amounts to an average reduction for each announcement of 3.7 basis points. If we distinguish events by year, the cumulative effect is substantially higher in 2010-2012 than in 2008 and 2009. In particular, whereas events happening in 2008 even exhibit a positive cumulative effect on the spread,[9] 2010 is the year with the highest cumulative and average effect in absolute value. By considering the nature of the operations announced, we can verify that SMP events feature the highest cumulative and average effect on the Italian spread, followed by the OMT and CBPP. The figures regarding FOR announcements show a large cumulative effect, but a rather small average effect. FRTFA and COLL events are instead associated with a negligible impact on the spread, both in terms of cumulative and average effect.

By extending the event window to two days (from the closing level of the spread on the day before to that on the day after the announcement), as in Neely (2010), we allow for delayed

[9]In Section 5 we provide some intuition for this empirical result.

reactions to news by market participants. The results are reported in the fourth column of Table 4. The pseudo p-values are now defined as the proportion of two-day spread changes during the period 2008-2012 that are larger in absolute value than the actual two-day change on the announcement day. The findings show that there has been a general increase (in absolute value) in the cumulative and average effects in comparison with a one-day window, both considering all the events and the events distinguished by year and type, suggesting a delayed reaction of financial market participants to ECB news. More specifically, the two-day window analysis implies a cumulative effect of all events of approximately minus 286 basis points. Except for events in 2010, the cumulative and average impact of ECB announcements is amplified substantially for all the years compared to the one-day window case. Also, these considerations remain valid when distinguishing the events by type, except for events related to CBPP operations.

Lastly, a different two-day window is adopted (from the closing level of the spread on the second day prior to the announcement to that on the day of the announcement) to better capture possible anticipation effects. The results are presented in the last column of Table 4. They indicate that ECB news have been generally subjected to some anticipation effect. In fact, the cumulative spread changes for all events are much higher in absolute value than using a one-day window, i.e. around minus 329 basis points. The same pattern is observable by looking at the cumulative and average effects when announcements are distinguished by year and type, with the exception of COLL events.

This section has provided some evidence on the effectiveness of ECB announcements of non-standard operations in reducing the Italian spread. The results are consistent with the idea that there were delayed market adjustments as well as a certain degree of anticipation by market participants. However, it is worth emphasizing some general limitations of event-study analyses. As has been stressed in the literature, it is necessary to assume that markets are informationally efficient, i.e. the majority of the impact of ECB unconventional policies on the spread does not occur when operations are actually implemented, but when market expectations about those measures are formed. Hence, the choice of the event window length is crucial, since it involves a trade-off between keeping the interval narrow to avoid the noise produced by extraneous information, and choosing a wider window to identify potential delayed and/or anticipated reactions of market participants. For this reason, the results obtained using two-day windows are, on the one hand, less accurate in comparison with those obtained using a one-day window, as extending the event window increases necessarily the noise in the estimates of the announcement effect. On the other hand, they are able to better capture market reactions that are incorporated with delay and/or anticipation in asset prices. The difficulties to identify accurately other relevant news affecting the spread and the anticipation effects of agents may potentially generate biases in the estimates of spread changes. Therefore, a more formal analysis is needed to better gauge the relationship between ECB news and the perceived Italian sovereign risk. In the next section, we use time-series econometrics to tackle these issues by controlling for expectations of market participants and for other factors that could affect the Italian spread vis-á-vis Germany.

5 The Time-Series Analysis

5.1 The Surprise Content of ECB Announcements

Since the expected part of monetary policy decisions is already priced into the market before a central bank announcement, it is only the surprise component that drives movements in yields (Kuttner, 2001; Fracasso et al., 2003). Therefore, to avoid the estimation bias that may arise from anticipated monetary policy decisions it is necessary to isolate the surprise component of monetary policy announcements. Moreover, the change in monetary policy could actually reflect the authorities' response to asset price developments. As stressed by Rigobon and Sack (2004), the causality between monetary policy decisions and asset prices runs in both directions. This endogeneity may introduce a significant bias in empirical estimations. To mitigate this problem it is useful to employ high-frequency data and focus on a narrow time interval around the policy decision. By shrinking the time period around the announcement, it becomes more likely that the monetary policy shock is the predominant driver of asset prices within that time window. If the variance of the monetary policy shock becomes infinitely large relative to the variances of the other disturbances, then the bias goes to zero (Rigobon and Sack, 2004).

Incorporating these considerations, we construct a monetary policy surprise indicator by adopting the technique recently proposed by Wright (2012) and employed by Glick and Leduc (2012). In particular, Wright (2012) uses intra-daily data on medium- and long-term interest rate bond futures to identify the surprise component of Federal Reserve announcements during the recent zero-lower-bound period. Futures prices are a natural and market-based proxy for expectations of central bank policy actions, and, therefore, have been frequently used in the literature to isolate monetary policy surprise shocks (Kuttner, 2001; Fleming and Piazzesi, 2005; Gürkaynak, 2005; Gürkaynak et al., 2005a,b; Mirkov, 2011).[10] It is worth noting that, by quantifying the communications' variable, it is also possible to better assess both the direction and magnitude of the shock in comparison with models employing dummy variables.

In the present paper, the monetary policy surprise shock is computed as yield changes of Italian long-term bond futures (EUREX-Euro BTP futures index) from 15 minutes before each ECB announcement to 1 hour and 45 minutes afterwards.[11] As in Wright (2012), yield changes are constructed as returns on the futures contract divided by the duration of the cheapest-to-deliver asset in the deliverable basket. Since EUREX futures on Italian government bonds have been introduced in September 2009, for events occurring earlier we employ EUREX-Euro Bund futures. This choice is justified by the fact that until the first months of 2010 Italian and German long-term bond futures prices have been very highly correlated. For comparison purposes, the monetary policy surprise indicator has been scaled to have a standard deviation of one. Positive changes in the index of BTP future prices are associated with positive values of the surprise indicator, while negative movements with negative values. The monetary policy surprise indicator for each ECB announcement of unconventional operations is reported in the

[10] Other ways to identify the unanticipated component of monetary policy announcements include the use of polls on market participant expectations (Ehrmann and Fratzscher, 2003, 2004, 2007a,b) and newspaper articles (Rosa, 2012).

[11] As stressed by Wright (2012), the selection of a quite wide window is supported by the fact that the events under scrutiny represent the interpretation of statements and speeches, as opposed as specific numerical values. Therefore, markets need more time to digest the new information and a relatively wide window is more suitable. Nevertheless, the use of narrower windows provides very similar results.

last column of Table 2.

5.2 The Econometric Methodology

This sub-section investigates, through the lenses of time-series econometrics, whether and to what extent ECB communications of non-standard operations have been capable of influencing the spread between the Italian and German long-term government bonds. More specifically, we investigate the effect of communications on the spread in a standard GARCH framework, originally proposed by Bollerslev (1986) to model time-varying volatility.[12] The conditional mean of the model is an augmented autoregressive process where both the lagged endogenous variables as well as the monetary policy surprise indicator are statistically insignificant for lag orders exceeding two and were omitted for reasons of parsimony:

$$\Delta S_t = \alpha + \sum_{i=1}^{2} \beta_i \Delta S_{t-i} + \sum_{i=0}^{2} \gamma_i UNC_{t-i} + \boldsymbol{\delta} \Delta \mathbf{X_t} + \varepsilon_t, \tag{1}$$

where ΔS_t is the first difference of spread between Italian and German government bonds,[13] UNC_t is the monetary policy surprise indicator calculated as explained in the previous subsection, and $\mathbf{X_t}$ represents a vector of controls. The lags of the monetary policy surprise indicator are introduced to capture possible delayed reactions of markets participants to non-conventional event shocks. Let the error process be such that $\varepsilon_t = \nu_t \sqrt{h_t}$, where ν_t is an i.i.d. sequence with zero mean and $\sigma_\nu^2 = 1$. The conditional variance of ε_t is modeled as an ARMA(1,1) process:

$$h_t = c + a\varepsilon_{t-1}^2 + bh_{t-1}. \tag{2}$$

The vector of control variables $\mathbf{X_t}$ includes: a) A volatility index for the euro area ($EuroVIX_t$) to control for financial turmoil, as in Arghyrou and Kontonikas (2012) and Glick and Leduc (2012). We expect a positive relationship between ΔS_t and $\Delta EuroVIX_t$. b) The *total stock market index* for the EU ($EUDS_t$) to control for market-wide business climate changes in the EU, as in De Bruyckere et al. (2012). We expect a negative sign for the coefficient of $EUDS_t$ in the model. c) The TED spread (TED_t), calculated as the three-month LIBOR rate less the US Treasury bill rate, to control for perceived credit risk in the global economy, as in Gerlach et al. (2010). The expected sign of the coefficient of this variable is positive. d) The credit default swap (CDS) of Greece ($CDSGreece_t$) to control for the turbulences due to the Greek sovereign crisis. We expect a positive relationship between this variable and the Italian spread.[14] Lastly, we also added a dummy variable (MPE_t) to account for the fact that five unconventional events listed in Table 2 coincide with a reduction of the key ECB interest rates.

[12] The estimation of a GARCH-M model reveals that the conditional volatility does not help to explain the spread, a finding in line with Taylor (1992). The results are available from the authors upon request.

[13] As in Gerlach et al. (2010), Attinasi et al. (2011), and Arghyrou and Kontonikas (2012).

[14] Due to statistical insignificance, a proxy for international risk aversion has been omitted from the analysis. This finding is in line with the evidence in Kozicki et al. (2011). Also, Bund futures turnover as a proxy for liquidity conditions has been found not to be statistically significant. Lastly, the presence of day dummies does not produce any substantial change in the results.

Parameters are estimated by (quasi-) maximum likelihood using the Broyden, Fletcher, Goldfarb and Shanno (BFGS) numerical algorithm with robust standard errors. The model is estimated using daily data obtained from the Thomson Reuters-Datastream database, covering the period 01:01:2008-31:12:2012. Details on the data employed in the analysis are reported in the Appendix.

5.3 The Results

The sample period from 2008 to 2012 covers both the global financial crisis as well as the European government debt crisis giving rise to the possibility of a different sovereign bond market reaction to ECB announcements. For instance, the zero-lower bound of interest rate was virtually reached only in the mid of 2009, and markets were repeatedly disappointed during 2008 following ECB refusals to move interest rates, while other central banks were cutting aggressively their policy rates. In this context, non-standard operations may have had undesired effects on market participants' behavior, as events perceived as a loosening of monetary policy could have been mainly considered by agents as a herald of unfavorable economic news (e.g. worsening macroeconomic outlook and increasing uncertainty), rather than a credible commitment by the ECB to improve market liquidity. This, in turn, may have raised the risk premium on Italian long-term treasuries and/or reduced German Bund rates within a 'flight to quality' context.

In early 2010, markets were again worrying about excessive national debt and demanded higher risk premia from countries with elevated debt levels, budget deficits and current account deficits. Of course, this further complicates the financing of budget deficits and servicing existing bonds, particularly when GDP growth was shrinking. On May, 8th, 2010, the EU launched the European Financial Stability Facility constructed to maintain financial market stability in the euro area by issuing financial assistance to threatened member states. This coincides with a structural break in the linear relationship between the spread change and the above mentioned regressors. A formal Chow break test reveals a highly significant F-statistic of 47.27 suggesting to estimate the GARCH models in two sub-samples, the first ranging from January, 2nd, 2008 to May, 7th, 2010 and the second ranging from May, 10th, 2010 to December, 31st, 2012.

Table 5 reports the parameter estimates of the GARCH model in equation (1) and (2). Ljung-Box (LB) Q-statistics were computed to test for remaining autocorrelation in standardized and squared standardized residuals. The p-values of the calculated LB-Q values show that the null hypothesis of no-autocorrelation up to five and ten orders cannot be rejected. The estimated coefficients of the variance equation are statistically significant at conventional levels (not reported here), revealing clustering and long memory of the spread volatility. From these observations we can conclude that GARCH models are reasonably specified. Turning to the estimates of the mean equation, we find that, in the first sub-sample, the sign of the control variables are as expected and statistically significant. For example, a one percent increase of the European risk measure $EuroVIX_t$ increases the Italian government bond spread by 28 basis points. To a lesser extent, the spread also reacts positively to changes of the global risk measure TED_t. In contrast, an improved economic outlook ($EUDS_t$) removes some pressure from Italian bonds. The figures also suggest some contagion effects from the Greek government debt crisis. Not surprisingly, the coefficient of the dummy variable MPE_t is negative, although statistically significant only at the ten percent level. With the transition to the second sub-sample, only

$EUDS_t$ and $CDSGreece_t$ remain significant.

[Table 5 about here]

The estimates of the monetary policy indicator are negative and highly significant in the second sub-sample suggesting that positive monetary policy surprises associated with ECB non-standard operations led to a substantial daily decline in the Italian spread. More precisely, a one standard deviation monetary policy surprise is estimated to lower the spread by around 13 basis points.[15] Since the coefficient of the surprise indicator is not subsequently reversed (as indicated by lower coefficient values for lags) our analysis suggests a permanent impact of monetary policy on the Italian government bond spread. In line with the above argumentation leading to a structural break in early 2010 we find an adverse influence of ECB non-standard operations in the first sub-sample. Consistently with the findings of the event-study analysis, monetary policy surprises are positively correlated with the spread before the structural break occurred, and negatively in the remaining years. Besides the above mentioned argumentation leading to the sub-sample estimation, which highlights the potential role of risk premium movements and expected - but not implemented - policy rate cuts, unconventional events right after the start of the crisis were mainly supplementary long-term refinancing operations and new liquidity-providing operations in foreign currency, which, as we will show in Table 7, do not exhibit any significant relationship with the Italian government bond spread. While confirming our approach, these results stress the importance of the prevailing market environment when predicting the influence of ECB policy measures.

Table 6 provides a more detailed view by distinguishing positive from negative monetary policy surprises. This is done by interacting the surprise monetary indicator with 0,1-dummies for positive and negative changes.

[Table 6 about here]

In the first sub-sample, positive surprises are associated with an increase in the spread, whereas negative surprises with a reduction generally reproducing the results of Table 5. It should be mentioned, however, that positive surprises exhibit a much larger influence on spreads than negative surprises, although coefficients are now not significant or only borderline significant. In the second sub-sample, we find a more symmetric contemporaneous influence of monetary surprises. A one standard deviation surprise affects the spread on average by 13 basis points in the expected direction. In case of negative shocks the impact is substantially diminished over the next trading day.

Within the event study analysis of section 4 we showed that the effect of ECB non-standard operations on the Italian spread seems to differ over time and across types of measure. While the sub-sample estimation of the GARCH model confirmed the time variation of results, we additionally check the robustness of the event study findings by distinguishing the policy events by typology. Due to the fact that some policy measures such as purchases of government bonds

[15] As stressed by Glick and Leduc (2012), the procedure to calculate the policy surprises does not ensure that a positive surprise will lower the Italian spread and a negative surprise will increase it. Since the surprise component is obtained using the futures on long-term Italian government bonds, the indicator is able to capture only the expectations of agents about ECB announcements. Long-term bond yields, and consequently the spread, can also be affected by other factors such as risk and term premia.

carried out under the *Securities Market Programme* or the *Outright Monetary Transactions* only occur in the second sub-sample we also provide a full-sample estimation.[16] Moreover, lags of higher than first order remain statistically insignificant and are skipped for parsimony. The estimation results are represented in Table 7.

[Table 7 about here]

From inspection of the full-sample estimation, we find that the ECB programs specially designed to improve conditions in euro area sovereign bond markets, i.e. the SMP and OMT, turn out to be most effective in influencing the Italian spread. A one standard deviation increase in the monetary policy indicator for these two programs is associated with a reduction in the spread of around 15-17 basis points. The coefficient of announcements of CBPP events is concurrently also negative and statistically significant, but is overcompensated by a significant reversal on the following trading day. Lastly, there is no evidence that measures aimed at expanding the collateral have affected the interest rate differential, a result that remains valid for the other three types of non-standard monetary policy measures. When looking at the second sub-sample the following results are worth mentioning. Compared to the first column of Table 7 the coefficient of events related to the extension of the collateral for banks becomes strongly statistically significant. According to these figures, COLL communications were even more effective in affecting the Italian spread than OMT events. Announcements of policies regarding foreign currency agreements, long-term refinancing operation and fixed rate tenders with full allotment are confirmed to play no role in spread movements. All in all, we found only weak evidence that news on measures specifically introduced to improve liquidity in banking markets were able to affect the Italian sovereign spread. These findings are somewhat in contrast to the hypothesis in Gerlach et al. (2010), and are probably related to the relative soundness of the Italian banking sector during the recent crisis. In fact, in countries with a relatively less vulnerable banking sector, aggregate risk fluctuations are likely to exert a smaller influence on sovereign risk movements via this banking channel.

6 Concluding Remarks

As the perceived sovereign risk of Italy started to increase in 2008, the differential between the Italian long-term government bond yields and their German counterparts widened to unprecedented levels since the introduction of the euro. At the same time, the European Central Bank launched a series of non-standard operations and programs aimed at restoring the proper functioning of interbank and financial markets, but also influencing the euro area sovereign debt problems. This paper has investigated how ECB announcements of unconventional operations affected the Italian spread vis-á-vis Germany during the last five years. We have explored this relationship empirically through an event-study as well as a time series analysis. The results from the event-study indicate that ECB communications about non-standard operations were able to reduce the sovereign solvency risk of Italy. Moreover, events taking place during the period 2010-2012 were more effective in shrinking the Italian spread vis-á-vis Germany in comparison

[16]News on CBPP operations only occur twice in the second sub-sample rendering parameter estimates unreliable. Thus, we skipped this variable from estimation.

with events occurring at the onset of the crisis in 2008-2009. Lastly, announcements of operations regarding the *Covered Bond Purchase Programmes*, the *Securities Market Programme*, and *Outright Monetary Transactions* are associated with a much stronger and significant reduction of the differential between Italian and German long-term bond yields as compared with other kinds of unconventional measures. By controlling for market participants' expectations and other factors, the findings from the econometric analysis confirm that ECB announcements of unconventional measures influenced significantly the Italian spread in the last five years. In addition, events happening in 2010-2012 and those related to the *Securities Market Programme*, *Outright Monetary Transactions*, and, to some extent, *Extensions of Eligible Assets* were remarkably powerful in affecting the yield differential. From a policy-making point of view, this paper has shown that the way the ECB 'bought time' during the last five years has been successful in downsizing the euro area sovereign debt crisis, at least for Italy.

References

Abbassi, P. and Linzert, T. (2011). The effectiveness of monetary policy in steering money market rates during the recent financial crisis. Working Paper Series 1328, European Central Bank.

Angelini, P., Nobili, A., and Picillo, C. (2011). The interbank market after August 2007: What has changed, and why? *Journal of Money, Credit and Banking*, 43(5):923–958.

Arghyrou, M. G. and Kontonikas, A. (2012). The EMU sovereign-debt crisis: Fundamentals, expectations and contagion. *Journal of International Financial Markets, Institutions and Money*, 22(4):658–677.

Attinasi, M., Checherita, C., and Nickel, C. (2011). What explains the surge in euro area sovereign spreads during the financial crisis of 2007-2009? In Kolb, R. W., editor, *Sovereign Debt: From Safety to Default*, pages 407–414. John Wiley & Sons, Inc.

Baumeister, C. and Benati, L. (2010). Unconventional monetary policy and the Great Recession - Estimating the impact of a compression in the yield spread at the zero lower bound. Working Paper Series 1258, European Central Bank.

Bayoumi, T., Goldstein, M., and Woglom, G. (1995). Do credit markets discipline sovereign borrowers? evidence from U.S. states. *Journal of Money, Credit and Banking*, 27(4):1046–1059.

Beirne, J., Dalitz, L., Ejsing, J., Grothe, M., Manganelli, S., Monar, F., Sahel, B., Sušec, M., Tapking, J., and Vong, T. (2011). The impact of the Eurosystem's covered bond purchase programme on the primary and secondary markets. Occasional Paper Series 122, European Central Bank.

Bernanke, B. S. and Reinhart, V. R. (2004). Conducting monetary policy at very low short-term interest rates. *The American Economic Review*, 94(2):85–90.

Blinder, A., Ehrmann, M., Fratzscher, M., de Haan, J., and Jansen, D. (2008). Central bank communication and monetary policy: A survey of theory and evidence. *Journal of Economic Literature*, pages 910–945.

Blinder, A. S. (2010). Quantitative easing: Entrance and exit strategies. *Federal Reserve Bank of St. Louis Review*, Nov-Dec:465–480.

Bollerslev, T. (1986). Generalized autoregressive conditional heteroskedasticity. *Journal of Econometrics*, 31(3):307–327.

Borio, C. and Disyatat, P. (2010). Unconventional monetary policies: an appraisal. *The Manchester School*, 78:53–89.

Bridges, J. and Thomas, R. (2012). The impact of QE on the UK economy - Some supportive monetarist arithmetic. Bank of England working papers 442, Bank of England.

Chen, H., Cúrdia, V., and Ferrero, A. (2012). The macroeconomic effects of large-scale asset purchase programmes. *The Economic Journal*, 122(564):F289–F315.

Christensen, J. H. E. and Rudebusch, G. D. (2012). The response of interest rates to US and UK Quantitative Easing. *The Economic Journal*, 122(564):F385–F414.

Craine, R. and Martin, V. L. (2008). International monetary policy surprise spillovers. *Journal of International Economics*, 75(1):180–196.

D'Amico, S., English, W., López-Salido, D., and Nelson, E. (2012). The Federal Reserve's large-scale asset purchase programmes: Rationale and effects. *The Economic Journal*, 122(564):F415–F446.

De Bruyckere, V., Gerhardt, M., Schepens, G., and Vander Vennet, R. (2012). Bank/sovereign risk spillovers in the European debt crisis. Working Paper Research 232, National Bank of Belgium.

de Haan, J., Oosterloo, S., and Schoenmaker, D. (2012). *Financial Markets and Institutions: A European Perspective.* Cambridge University Press.

De Santis, R. A. (2012). The Euro area sovereign debt crisis: Safe haven, credit rating agencies and the spread of the fever from Greece, Ireland and Portugal. Working Paper Series 1419, European Central Bank.

Doh, T. (2010). The efficacy of large-scale asset purchases at the zero lower bound. *Federal Reserve Bank of Kansas City Economic Review*, (Q II):5–34.

Ehrmann, M. and Fratzscher, M. (2003). Monetary policy announcements and money markets: A transatlantic perspective. *International Finance*, 6(3):309–328.

Ehrmann, M. and Fratzscher, M. (2004). Taking stock: Monetary policy transmission to equity markets. *Journal of Money, Credit and Banking*, 36(4):719–737.

Ehrmann, M. and Fratzscher, M. (2007a). Communication by central bank committee members: Different strategies, same effectiveness? *Journal of Money, Credit and Banking*, 39(2-3):509–541.

Ehrmann, M. and Fratzscher, M. (2007b). The timing of central bank communication. *European Journal of Political Economy*, 23(1):124–145.

Falagiarda, M. (2013). Evaluating Quantitative Easing: A DSGE approach. MPRA Paper 49457, University Library of Munich.

Fleming, M. and Piazzesi, M. (2005). Monetary policy tick-by-tick. *Unpublished manuscript.*

Fracasso, A., Genberg, H. J., and Wyplosz, C. (2003). *How do central banks write? An evaluation of inflation reports by inflation targeting central banks*, volume 2. CEPR Publications.

Gagnon, J., Raskin, M., Remache, J., and Sack, B. (2011). The financial market effects of the Federal Reserve's large-scale asset purchases. *International Journal of Central Banking*, 7(1):3–43.

Gerlach, S., Schulz, A., and Wolff, G. B. (2010). Banking and sovereign risk in the Euro area. CEPR Discussion Papers 7833.

Giannone, D., Lenza, M., Pill, H., and Reichlin, L. (2011). Non-standard monetary policy measures and monetary developments. In Chadha, J. and Holly, S., editors, *Interest Rates, Prices and Liquidity: Lessons from the Financial Crisis*, chapter 8.

Giordano, R., Pericoli, M., and Tommasino, P. (2013). Pure or wake-up-call contagion? Another look at the EMU sovereign debt crisis. *International Finance*, 16(2):131–160.

Glick, R. and Leduc, S. (2012). Central bank announcements of asset purchases and the impact on global financial and commodity markets. *Journal of International Money and Finance*, 31(8):2078–2101.

Goldstein, M. and Woglom, G. (1991). *Market-based fiscal discipline in monetary unions: Evidence from the US municipal bond market*, volume 89. International Monetary Fund.

Gürkaynak, R. S. (2005). Using federal funds futures contracts for monetary policy analysis. Finance and Economics Discussion Series 2005-29, Board of Governors of the Federal Reserve System.

Gürkaynak, R. S., Sack, B., and Swanson, E. (2005a). Do actions speak louder than words? The response of asset prices to monetary policy actions and statements. *International Journal of Central Banking*, 1(1):55–93.

Gürkaynak, R. S., Sack, B., and Swanson, E. (2005b). The sensitivity of long-term interest rates to economic news: Evidence and implications for macroeconomic models. *The American Economic Review*, 95(1):425–436.

Hamilton, J. D. and Wu, J. C. (2012). The effectiveness of alternative monetary policy tools in a zero lower bound environment. *Journal of Money, Credit and Banking*, 44:3–46.

Joyce, M. A. S., Lasaosa, A., Stevens, I., and Tong, M. (2011a). The financial market impact of quantitative easing in the United Kingdom. *International Journal of Central Banking*, 7(3):113–161.

Joyce, M. A. S., Miles, D., Scott, A., and Vayanos, D. (2012). Quantitative easing and unconventional monetary policy - An introduction. *The Economic Journal*, 122(564):F271–F288.

Joyce, M. A. S. and Tong, M. (2012). QE and the gilt market: a disaggregated analysis. *The Economic Journal*, 122(564):F348–F384.

Joyce, M. A. S., Tong, M., and Woods, R. (2011b). The United Kingdom's quantitative easing policy: Design, operation and impact. *Bank of England Quarterly Bulletin*, Q3:200–212.

Kapetanios, G., Mumtaz, H., Stevens, I., and Theodoridis, K. (2012). Assessing the economy-wide effects of quantitative easing. *The Economic Journal*, 122(564):F316–F347.

Klyuev, V., de Imus, P., and Srinivasan, K. (2009). Unconventional choices for unconventional times: credit and quantitative easing in advanced economies. IMF Staff Position Note SPN/09/27.

Kozicki, S., Santor, E., and Suchanek, L. (2011). Central bank balance sheets and long-term forward rates. In Chadha, J. and Holly, S., editors, *Interest Rates, Prices and Liquidity: Lessons from the Financial Crisis*, chapter 7.

Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). The effects of quantitative easing on interest rates: channels and implications for policy. NBER Working Papers 17555, National Bureau of Economic Research.

Krugman, P. R. (1998). It's baaack: Japan's slump and the return of the liquidity trap. *Brookings Papers on Economic Activity*, 1998(2):137–205.

Kuttner, K. N. (2001). Monetary policy surprises and interest rates: Evidence from the Fed funds futures market. *Journal of Monetary Economics*, 47(3):523–544.

Lenza, M., Pill, H., and Reichlin, L. (2010). Monetary policy in exceptional times. *Economic Policy*, 25(62):295–339.

Meaning, J. and Zhu, F. (2011). The impact of recent central bank asset purchase programmes. *BIS Quarterly Review*, December.

Meier, A. (2009). Panacea, curse, or nonevent? Unconventional monetary policy in the United Kingdom. IMF Working Papers 09/163, International Monetary Fund.

Mirkov, N. (2011). The US term premia around the FOMC decisions. Working Paper Series 139, School of Finance - University of St.Gallen.

Neely, C. J. (2010). The large scale asset purchases had large international effects. Working Papers 2010-018, Federal Reserve Bank of St. Louis.

Orphanides, A. (2004). Monetary policy in deflation: the liquidity trap in history and practice. *The North American Journal of Economics and Finance*, 15(1):101–124.

Peersman, G. (2011). Macroeconomic effects of unconventional monetary policy in the Euro area. Working Paper Series 1397, European Central Bank.

Rigobon, R. and Sack, B. (2004). The impact of monetary policy on asset prices. *Journal of Monetary Economics*, 51(8):1553–1575.

Rosa, C. (2012). How "unconventional" are large-scale asset purchases? The impact of monetary policy on asset prices. Staff Reports 560, Federal Reserve Bank of New York.

Schuknecht, L., Von Hagen, J., and Wolswijk, G. (2009). Government risk premiums in the bond market: EMU and Canada. *European Journal of Political Economy*, 25(3):371–384.

Svensson, L. E. O. (2003). Escaping from a liquidity trap and deflation: the foolproof way and others. *The Journal of Economic Perspectives*, 17(4):145–166.

Swanson, E. T. (2011). Let's twist again: A high-frequency event-study analysis of Operation Twist and its implications for QE2. *Brookings Papers on Economic Activity*, 42(1):151–207.

Taylor, M. P. (1992). Modelling the yield curve. *The Economic Journal*, 102(412):524–537.

Tobin, J. (1958). Liquidity preference as behavior towards risk. *Review of Economic Studies*, 25(2):65–86.

Vayanos, D. and Vila, J.-L. (2009). A preferred-habitat model of the term structure of interest rates. Working Paper 15487, National Bureau of Economic Research.

Wright, J. H. (2012). What does monetary policy do to long-term interest rates at the zero lower bound? *The Economic Journal*, 122(564):F447–F466.

Tables and Figures

Table 1: Details on securities holdings acquired under the SMP

Issuer country	Outstanding amounts		Average remaining maturity (in years)
	Nominal amount (€ billion)	Book value (€ billion)	
Greece	33.9	30.8	3.6
Ireland	14.2	13.6	4.6
Italy	102.8	99.0	4.5
Portugal	22.8	21.6	3.9
Spain	44.3	43.7	4.1
Total	218.0	208.7	4.3

Notes: The table shows the breakdown of the Eurosystems SMP holdings as at 31 December 2012, per country of issuer, indicated at nominal value, book value and average remaining maturity. **Source:** ECB Press Release, 21 February 2013.

Table 2: ECB unconventional monetary policy programs announcements

Date	Time (CET)	Event	Type	Description	Monetary surprise
10/01/2008	3:00 pm	PR	FOR	The GovC decided to conduct US dollar liquidity-providing operations	-0.089
07/02/2008	2:30 pm	PC	LTRO	The GovC decided to renew two outstanding supplementary longer-term refinancing operations	-0.088
11/03/2008	3:00 pm	PR	FOR	The GovC decided to conduct US dollar liquidity-providing operations	0.040
28/03/2008	3:00 pm	PR	LTRO	The GovC decided to conduct supplementary longer-term refinancing operations	-0.101
02/05/2008	3:00 pm	PR	FOR	The GovC decided to enhance US dollar liquidity-providing operations	-0.355
30/07/2008	3:00 pm	PR	FOR	The GovC decided to enhance US dollar liquidity-providing operations	0.125
31/07/2008	3:00 pm	PR	LTRO	The GovC decided to renew two outstanding supplementary longer-term refinancing operations	0.229
04/09/2008	2:30 pm	PC	LTRO	The GovC decided to renew three outstanding supplementary longer-term refinancing operations	-0.175
18/09/2008	9:00 am	PR	FOR	The GovC decided to enhance US dollar liquidity-providing operations	0.114
26/09/2008	8:00 am	PR	FOR	The GovC decided to enhance US dollar liquidity-providing operations	0.357
29/09/2008	4:00 pm	PR	FOR	The GovC decided to double the temporary swap lines with the Fed	0.444
07/10/2008	2:15 pm	PR	LTRO, FOR	The GovC decided to enhance a longer-term refinancing operation and expand US dollar liquidity-providing operations	-0.051
08/10/2008*	1:00 pm	PR	FRTFA	The GovC decided to adopt a fixed rate tender procedure with full allotment	-0.406

Table 2: (continued)

13/10/2008	8:00 am	PR	FOR	The GovC decided to conduct US dollar liquidity-providing operations	-0.334
15/10/2008	3:00 pm	PR	COLL, LTRO, FOR	The GovC decided to expand the list of assets eligible as collateral, enhance the provision of longer-term refinancing operations, and provide US dollar liquidity through foreign exchange swaps	-0.367
18/12/2008	3:00 pm	PR	FRTFA	The GovC decided that the main refinancing operations will continue to be carried out through a fixed rate tender procedure with full allotment for as long as needed	0.360
19/12/2008	3:00 pm	PR	FOR	The GovC decided to continue conducting US dollar liquidity-providing operations	0.066
03/02/2009	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangements with the Fed	-0.337
05/03/2009*	2:30 pm	PC	FRTFA, LTRO	The GpvC decided to continue the fixed rate tender procedure with full allotment for all main refinancing operations, special-term refinancing operations and supplementary and regular longer-term refinancing operations for as long as needed	-0.056
19/03/2009	3:00 pm	PR	FOR	The GovC decided to continue conducting US dollar liquidity-providing operations	-0.226
06/04/2009	3:00 pm	PR	FOR	The GovC decided to establish a temporary reciprocal currency arrangement (swap line) with the Fed	0.125
07/05/2009*	2:30 pm	PC, PR	LTRO, CBPP	The GovC decided to proceed with the ECS. In particular, the GovC decided to purchase euro-denominated covered bonds issued in the euro area, and to conduct liquidity-providing longer-term refinancing operations with a maturity of one year	-0.295
04/06/2009	2:30 pm	PC	CBPP	The GovC decided upon the technical modalities of the CBPP1	-0.544
25/06/2009	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangements with the Fed	0.030
24/09/2009	3:00 pm	PR	FOR	The GovC decided to continue conducting US dollar liquidity-providing operations	0.245
03/12/2009	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue conducting its main refinancing operations as fixed rate tender procedures with full allotment for as long as is needed, and to enhance the provision of longer-term refinancing operations	0.036
04/03/2010	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue conducting its main refinancing operations as fixed rate tender procedures with full allotment for as long as is needed, and to return to variable rate tender procedures in the regular 3-month longer-term refinancing operations	0.247
10/05/2010	Night 09/05	PR	SMP, FOR, LTRO	The GovC decided to proceed with the SMP, to reactivate the temporary liquidity swap lines with the Fed, to adopt a fixed-rate tender procedure with full allotment in the regular 3-month longer-term refinancing operations, and to conduct new special longer-term refinancing operations	2.695
10/06/2010	2:30 pm	PC	LTRO	The GovC decided to adopt a fixed rate tender procedure with full allotment in the regular 3-month longer-term refinancing operations	-0.010

Table 2: (continued)

02/09/2010	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue to conduct its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	-0.029
02/12/2010	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue to conduct its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	-0.043
17/12/2010	3:00 pm	PR	FOR	The ECB announced a temporary swap facility with the Bank of England	-0.019
21/12/2010	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangements with the Fed	0.106
03/03/2011	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue to conduct its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	-0.456
09/06/2011	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue to conduct its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	0.151
29/06/2011	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangements with the Fed	-0.133
04/08/2011	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue conducting its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment, and to conduct a liquidity-providing supplementary longer-term refinancing operation with a maturity of six months as a fixed rate tender procedure with full allotment	0.012
08/08/2011	Night 07/08	PR	SMP	The GovC decided to actively implement its Securities Markets Programme for Italy and Spain	4.815
25/08/2011	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangement with the Bank of England	-0.074
15/09/2011	3:00 pm	PR	FOR	The GovC decided to conduct three US dollar liquidity-providing operations in coordination with other central banks	0.043
06/10/2011	2:30 pm	PC	FRTFA, LTRO, CBPP	The GovC decided to continue conducting its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment, to conduct two liquidity-providing supplementary longer-term refinancing operation with a maturity of twelve and thirteen months as a fixed rate tender procedure with full allotment, and to launch a new covered bond purchase program (CBPP2)	-0.011
03/11/2011*	3:00 pm	PR	CBPP	The GovC decided upon the technical modalities of CBPP2	-0.138

Table 2: (continued)

30/11/2011	3:00 pm	PR	FOR	The GovC decided in cooperation with other central banks the establishment of a temporary network of reciprocal swap lines	1.510
08/12/2011*	2:30 pm	PC	LTRO, COLL	The GovC decided to conduct two longer-term refinancing operations with a maturity of three years and to increase collateral availability	-1.263
09/02/2012	2:30 pm	PC	COLL	The GovC approved specific national eligibility criteria and risk control measures for the temporary acceptance in a number of countries of additional credit claims as collateral in Eurosystem credit operations.	1.085
06/06/2012	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue to conduct its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	0.034
22/06/2012	3:00 pm	PR	COLL	The GovC took further measures to increase collateral availability for counterparties	0.170
26/07/2012	12:00 noon	SP	OMT	Draghi's *London speech* ("...the ECB is ready to do whatever it takes to preserve the euro.")	2.541
02/08/2012	2:30 pm	PC	OMT	The GovC announced that may undertake outright open market operations of a size adequate to reach its objective. Markets disappointed for lack of details about OMT	-3.084
27/08/2012	5:00 pm	SP	OMT	Asmussen's *Hamburg speech* supporting the new bond purchase program	0.046
06/09/2012	2:30 pm	PC	OMT, COLL	The GovC announced the technical details of OMT and decided on additional measures to preserve collateral availability	0.455
12/09/2012	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangement with the Bank of England	0.377
06/12/2012	2:30 pm	PC	FRTFA, LTRO	The GovC decided to continue conducting its main refinancing operations as fixed rate tender procedures with full allotment for as long as necessary, and to conduct 3-month longer-term refinancing operations as fixed rate tender procedures with full allotment	0.547
13/12/2012	3:00 pm	PR	FOR	The GovC decided to extend the liquidity swap arrangements with the Fed	-0.062

Notes: The table reports all the identified events related to ECB unconventional operations over the period 2008-2012. For each event we indicate the day and the exact time when it was announced, the type of the announcement, the nature of the measure announced and a brief description. PC indicates Press Conference; PR indicates Press Release; SP indicates Speech. * denotes that the event coincides with a reduction of the key ECB interest rates.

Table 3: Standard deviations of daily basis point changes in the spread

	Event days	Non-event days	Non-event Thursdays	Non-event GovC days
Entire sample	18.12	8.82	8.10	10.30
2008	5.11	2.94	2.47	3.02
2009	4.17	4.15	4.40	4.20
2010	19.42	5.43	5.87	9.44
2011	25.88	13.59	11.70	5.61
2012	24.18	12.17	11.82	20.21

Table 4: Effects of ECB unconventional monetary policy operations on the Italian spread

Date	Type	1-day window	2-day window (lagged effects)	2-day window (anticipation effects)
10/01/2008	FOR	2.6	1.5	4.3
		(0.56)	(0.81)	(0.55)
07/02/2008	LTRO	−0.2	−1.9	0.5
		(0.94)	(0.76)	(0.94)
11/03/2008	FOR	−3.5	−4.7	−2.8
		(0.48)	(0.52)	(0.68)
28/03/2008	LTRO	−1.8	−1.7	−3.1
		(0.66)	(0.79)	(0.65)
02/05/2008	FOR	−1.0	−2.1	−1.0
		(0.80)	(0.74)	(0.87)
30/07/2008	FOR	−0.3	−2.4	2.2
		(0.93)	(0.72)	(0.73)
31/07/2008	LTRO	−2.1	9.5	−2.4
		(0.62)	(0.30)	(0.72)
04/09/2008	LTRO	2.1	5.0	2.4
		(0.62)	(0.50)	(0.72)
18/09/2008	FOR	5.2	−3.6	6.6
		(0.34)	(0.61)	(0.42)
26/09/2008	FOR	4.0	21.0	2.2
		(0.44)	(0.10)	(0.73)
29/09/2008	FOR	17.0	16.0	21.0
		(0.07)	(0.15)	(0.10)
07/10/2008	LTRO, FOR	0.2	3.7	2.6
		(0.94)	(0.60)	(0.70)
08/10/2008*	FRTFA	3.5	3.2	3.7
		(0.48)	(0.64)	(0.60)
13/10/2008	FOR	−6.0	−12.3	−5.4
		(0.29)	(0.22)	(0.49)
15/10/2008	COLL, LTRO, FOR	−4.4	−2.9	−10.7
		(0.41)	(0.67)	(0.26)
18/12/2008	FRTFA	−0.2	1.5	1.8
		(0.94)	(0.81)	(0.77)
19/12/2008	FOR	1.7	2.2	1.5
		(0.68)	(0.73)	(0.81)
03/02/2009	FOR	−6.6	−18.6	−12.4
		(0.26)	(0.12)	(0.22)
05/03/2009*	FRTFA, LTRO	0.4	7.2	−5.7
		(0.90)	(0.39)	(0.47)
19/03/2009	FOR	4.6	−1.9	3.3
		(0.39)	(0.76)	(0.63)
06/04/2009	FOR	1.3	4.1	−8.6
		(0.74)	(0.57)	(0.33)
07/05/2009*	LTRO, CBPP	−10.0	−15.1	−12.7
		(0.15)	(0.16)	(0.21)
04/06/2009	CBPP	3.4	−1.2	3.5
		(0.50)	(0.85)	(0.62)
25/06/2009	FOR	−1.2	−1.7	−4.2
		(0.76)	(0.79)	(0.56)
24/09/2009	FOR	0.6	1.9	2.4
		(0.86)	(0.76)	(0.72)
03/12/2009	FRTFA, LTRO	−1.1	−8.1	−2.1
		(0.78)	(0.35)	(0.74)
04/03/2010	FRTFA, LTRO	−0.2	−3.8	−1.7

Table 4: (continued)

		(0.94)	(0.59)	(0.79)
10/05/2010	SMP, FOR, LTRO	−50.5	−49.2	−42.1
		(0.00)	(0.01)	(0.02)
10/06/2010	LTRO	−17.1	−13.1	−34.3
		(0.06)	(0.20)	(0.04)
02/09/2010	FRTFA, LTRO	−6.5	−11.6	−17.4
		(0.27)	(0.24)	(0.13)
02/12/2010	FRTFA, LTRO	−17.5	−19.4	−44.5
		(0.06)	(0.11)	(0.02)
17/12/2010	FOR	5.6	9.9	7.1
		(0.31)	(0.29)	(0.39)
21/12/2010	FOR	3.7	6.2	8.0
		(0.46)	(0.44)	(0.36)
03/03/2011	FRTFA, LTRO	0.0	−1.7	−2.0
		(0.98)	(0.79)	(0.75)
09/06/2011	FRTFA, LTRO	7.3	11.2	10.7
		(0.23)	(0.25)	(0.26)
29/06/2011	FOR	−10.2	−18.7	−14.2
		(0.15)	(0.12)	(0.18)
04/08/2011	FRTFA, LTRO	18.3	2.3	14.6
		(0.05)	(0.73)	(0.17)
08/08/2011	SMP	−71.4	−86.4	−87.4
		(0.00)	(0.00)	(0.00)
25/08/2011	FOR	0.2	6.4	0.9
		(0.94)	(0.43)	(0.88)
15/09/2011	FOR	−9.4	−16.0	−27.8
		(0.17)	(0.15)	(0.06)
06/10/2011	FRTFA, LTRO, CBPP	−16.9	−14.8	−22.3
		(0.07)	(0.17)	(0.09)
03/11/2011*	CBPP	−4.7	14.6	−8.5
		(0.38)	(0.17)	0.34
30/11/2011	FOR	−12.4	−44.1	−11.9
		(0.12)	(0.02)	(0.23)
08/12/2011*	LTRO, COLL	45.2	41.7	64.7
		(0.01)	(0.03)	(0.01)
09/02/2012	COLL	−13.2	4.8	−18.8
		(0.11)	(0.52)	(0.12)
06/06/2012	FRTFA, LTRO	−10.3	−15.9	−11.9
		(0.14)	(0.15)	(0.23)
22/06/2012	COLL	4.6	34.7	7.4
		(0.39)	(0.04)	(0.38)
26/07/2012	OMT	−43.7	−61.7	−58.9
		(0.01)	(0.01)	(0.01)
02/08/2012	OMT	41.2	11.2	22.7
		(0.01)	(0.25)	(0.09)
27/08/2012	OMT	−24.3	−13.1	5.0
		(0.03)	(0.20)	(0.50)
06/09/2012	OMT, COLL	−29.0	−54.5	−45.3
		(0.02)	(0.01)	(0.02)
12/09/2012	FOR	−14.1	−11.5	−22.5
		(0.10)	(0.24)	(0.09)
06/12/2012	FRTFA, LTRO	16.1	13.9	24.0
		(0.07)	(0.18)	(0.08)
13/12/2012	FOR	−0.4	−7.1	−10.1
		(0.90)	(0.39)	(0.28)

Table 4: (continued)

All events	Sum	−201.4	−286.7	−329.6
	Avg	−3.7	−5.3	−6.1
		(0.46)	(0.49)	(0.44)
Events distinguished by year				
Events 2008	Sum	16.8	32.0	23.4
	Avg	1.0	1.9	1.38
		(0.81)	(0.77)	(0.83)
Events 2009	Sum	−8.6	−33.0	−36.5
	Avg	−1.0	−3.7	−4.1
		(0.81)	(0.61)	(0.57)
Events 2010	Sum	−82.5	−81.0	−124.9
	Avg	−11.8	−11.6	−17.8
		(0.13)	(0.24)	(0.13)
Events 2011	Sum	−54.0	−105.5	−83.2
	Avg	−4.9	−9.6	−7.6
		(0.36)	(0.30)	(0.37)
Events 2012	Sum	−73.1	−99.2	−108.4
	Avg	−7.3	−9.9	−10.8
		(0.23)	(0.29)	(0.26)
Events distinguished by type				
FOR events	Sum	−73.3	−123.5	−111.6
	Avg	−2.9	−4.9	−4.5
		(0.53)	(0.50)	(0.54)
FRTFA events	Sum	−7.1	−36.0	−52.8
	Avg	−0.5	−2.8	−4.1
		(0.87)	(0.69)	(0.57)
LTRO events	Sum	−49.0	−64.7	−93.4
	Avg	−2.3	−3.1	−4.4
		(0.59)	(0.66)	(0.54)
COLL events	Sum	3.2	23.8	−2.7
	Avg	0.6	4.8	−0.5
		(0.84)	(0.52)	(0.93)
CBPP events	Sum	−28.2	−16.5	−40.0
	Avg	−7.1	−4.1	−10.0
		(0.24)	(0.56)	(0.29)
SMP events	Sum	−121.9	−135.6	−129.5
	Avg	−61.0	−67.8	−64.8
		(0.00)	(0.00)	(0.01)
OMT events	Sum	−55.8	−118.1	−76.5
	Avg	−14.0	−29.5	−19.1
		(0.10)	(0.05)	(0.11)

Notes: The table reports changes in the Italian spread around each ECB announcement, as well as the cumulative and average effect over all announcements. Moreover, it shows the cumulative and average effect when distinguishing events by year and type of the operation. Three different event windows are used. "P-values" in parentheses indicate the proportion of n-day spread changes during the period 01:01:2008-31:12:2012 that were larger in absolute value than the actual change in the n-day period around the event. * denotes that the event coincides with a reduction of the key ECB interest rates.

Table 5: Parameter estimates - All events

	01/02/08 to 05/07/10	05/10/10 to 12/31/12
Constant	0.036(0.109)	0.310(0.231)
ΔS_{t-1}	0.215(0.042)***	0.238(0.035)***
ΔS_{t-2}	$-0.032(0.048)$	$-0.120(0.032)^{***}$
UNC_t	2.199(3.396)	$-13.033(1.279)^{***}$
UNC_{t-1}	8.223(2.912)***	3.348(1.544)**
UNC_{t-2}	0.587(2.714)	$-2.327(1.025)^{**}$
$\Delta EuroVIX_t$	0.279(0.127)**	0.450(0.296)
MPE_t	$-5.749(3.231)^{*}$	16.137(12.342)
$\Delta EUDS_t$	$-0.017(0.008)^{**}$	$-0.160(0.026)^{***}$
ΔTED_t	0.044(0.017)***	$-0.058(0.129)$
$\Delta CDSGreece_t$	0.076(0.016)***	0.001(0.001)**
Log-Likelihood	-1506.49	-2415.81
$Q(5)$	0.5223	0.3300
$Q(10)$	0.6928	0.3382
$Q^2(5)$	0.4112	0.2468
$Q^2(10)$	0.6375	0.7169
Observations	610	691

Notes: GARCH(1,1) regressions of daily basis point change in the spread. *** (**, *) indicates statistical significance at the 1 (5, 10) percent level. Robust standard errors in parenthesis. $Q(5)$ and $Q(10)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the standardized residuals up to the 5th and 10th order, respectively. $Q^2(5)$ and $Q^2(10)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the squared standardized residuals up to the 5th and 10th order, respectively.

Table 6: Parameter estimates - Events distinguished by surprise direction

	01/02/08 to 05/07/10	05/10/10 to 12/31/12
Constant	$-0.010(0.122)$	$0.335(0.238)$
ΔS_{t-1}	$0.09(0.040)^{***}$	$0.236(0.037)^{***}$
ΔS_{t-2}	$-0.034(0.044)$	$-0.122(0.035)^{***}$
$UNCpos_t$	$11.363(8.334)$	$-13.494(1.439)^{***}$
$UNCpos_{t-1}$	$5.511(7.011)$	$1.648(1.750)$
$UNCpos_{t-2}$	$-1.651(5.464)$	$-2.089(0.969)^{**}$
$UNCneg_t$	$1.353(3.067)$	$12.321(1.111)^{***}$
$UNCneg_{t-1}$	$-5.153(3.115)^{*}$	$-9.506(0.947)^{***}$
$UNCneg_{t-2}$	$-0.843(3.618)$	$3.484(1.338)^{***}$
$\Delta EuroVIX_t$	$0.285(0.129)^{**}$	$0.442(0.232)^{*}$
MPE_t	$-6.712(3.420)^{**}$	$16.461(11.344)$
$\Delta EUDS_t$	$-0.016(0.008)^{**}$	$-0.160(0.021)^{***}$
ΔTED_t	$0.041(0.014)^{***}$	$-0.071(0.126)$
$\Delta CDSGreece_t$	$0.077(0.013)^{***}$	$0.001(0.001)^{**}$
Log-Likelihood	-1503.75	-2413.14
$Q(5)$	0.3688	0.4009
$Q(10)$	0.3934	0.4793
$Q^2(5)$	0.26212	0.2837
$Q^2(10)$	0.7192	0.7466
Observations	610	691

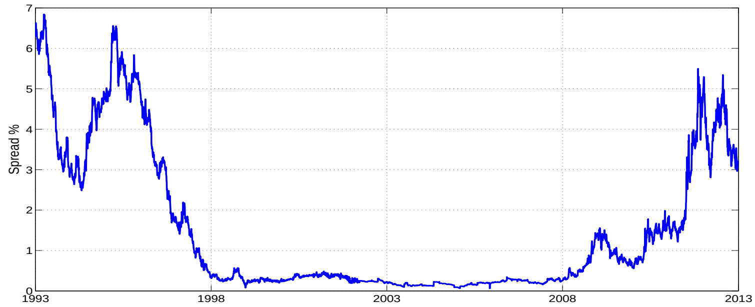
Notes: GARCH(1,1) regressions of daily basis point change in the spread. *** (**, *) indicates statistical significance at the 1 (5, 10) percent level. Robust standard errors in parenthesis. $Q(5)$ and $Q(10)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the standardized residuals up to the 5th and 10th order, respectively. $Q^2(5)$ and $Q^2(10)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the squared standardized residuals up to the 4th and 12th order, respectively.

Table 7: Parameter estimates - Events distinguished by type

	01/02/08 to 12/31/12	05/10/10 to 12/31/12
Constant	0.061(0.102)	0.331(0.239)
ΔS_{t-1}	0.237(0.031)***	0.223(0.041)***
ΔS_{t-2}	$-0.092(0.032)^{***}$	$-0.111(0.042)^{***}$
FOR_t	2.677(5.663)	14.578(9.449)
FOR_{t-1}	5.913(4.001)	6.457(11.668)
$FRTFA_t$	2.147(8.794)	13.028(13.471)
$FRTFA_{t-1}$	2.507(24.284)	13.466(15.353)
$LTRO_t$	2.431(5.077)	$-8.883(8.959)$
$LTRO_{t-1}$	4.706(6.494)	$-3.335(11.052)$
$COLL_t$	$-10.909(7.412)$	$-15.071(5.049)^{***}$
$COLL_{t-1}$	8.620(7.215)	6.740(6.425)
$CBPP_t$	$-6.046(2.181)^{***}$	$--$
$CBPP_{t-1}$	8.181(1.962)***	$--$
SMP_t	$-17.054(2.023)^{***}$	$-16.198(0.520)^{***}$
SMP_{t-1}	$-2.220(2.355)$	0.182(0.901)
OMT_t	$-15.163(0.771)^{***}$	$-13.486(1.067)^{***}$
OMT_{t-1}	5.569(3.097)*	4.791(2.741)*
$\Delta EuroVIX_t$	0.471(0.151)***	0.535(0.250)**
MPE_t	$-9.108(3.402)^{***}$	$-9.254(14.796)$
$\Delta EUDS$	$-0.027(0.009)^{***}$	$-0.153(0.022)^{***}$
ΔTED_t	0.043(0.013)***	$-0.032(0.124)$
$\Delta CDSGreece_t$	0.002(0.001)***	0.001(0.001)**
Log-Likelihood	-4009.77	-2410.42
$Q(5)$	0.7055	0.5465
$Q(10)$	0.7953	0.6220
$Q^2(5)$	0.4749	0.2104
$Q^2(10)$	0.4859	0.6214
Observations	1301	691

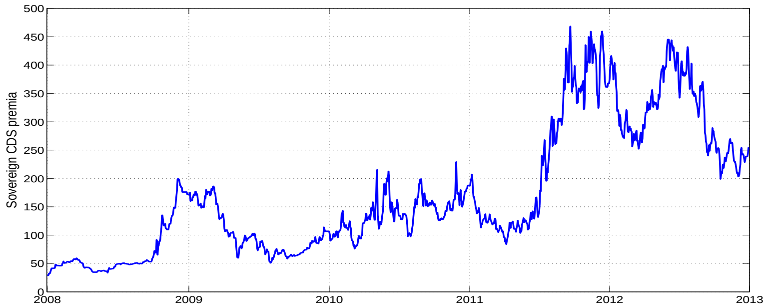
Notes: GARCH(1,1) regressions of daily basis point change in the spread. *** (**, *) indicates statistical significance at the 1 (5, 10) percent level. Robust standard errors in parenthesis. $Q(4)$ and $Q(12)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the standardized residuals up to the 4th and 12th order, respectively. $Q^2(4)$ and $Q^2(12)$ is the statistical significance of the Ljung-Box Q test for the autocorrelations of the squared standardized residuals up to the 4th and 12th order, respectively.

Figure 1: Evolution of the Italian spread vis-á-vis Germany



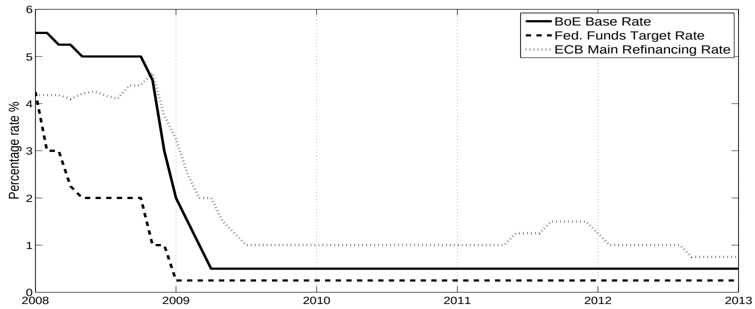
Source: Thomson Reuters-Datastream.

Figure 2: Italian sovereign CDS premia (levels)



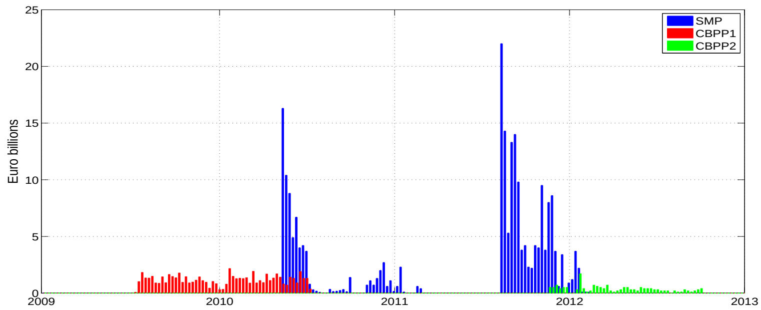
Source: Thomson Reuters-Datastream.

Figure 3: Evolution of the policy rate in the UK, the US and the euro area



Source: Thomson Reuters-Datastream.

Figure 4: ECB purchases under the CBPP1, CBPP2 and SMP



Source: ECB.

Appendix: The Data

Daily data (obtained from Thomson Reuters-Datastream):

- Long-term bond yield for Italy: Italy Benchmark Bond 10 YR - Redemption Yield (Datastream mnemonic: ITBRYLD)
- Long-term bond yield for Germany: Germany Benchmark Bond 10 YR - Redemption Yield (Datastream mnemonic: BDBRYLD)
- EuroVIX: VSTOXX volatility index (Datastream mnemonic: VSTOXXI)
- Total stock market index for the EU: EU-DS Market (Datastream mnemonic: TOTMKEU)
- TED spread: TED spread rate - middle rate (Datastream mnemonic: TRTEDSP)
- CDS Greece: Greece Senior 10 Year Credit Default Swap (Datastream mnemonic: GRGVTSX)
- CDS Italy: Republic of Italy Senior CR 10 Year (Datastream mnemonic: ITGAEAC)

Intraday data (obtained from www.tickdatamarket.com):

- Bund futures: EUREX Euro-Bund Futures
- BTP futures: EUREX Long-term Euro-BTP Futures

A DSGE model with Endogenous Term Structure

Matteo Falagiarda* Massimiliano Marzo†

First version: May 2012
This version: January 2013‡

Abstract

In this paper, we propose a Dynamic Stochastic General Equilibrium (DSGE) model with the term structure of interest rates drawing on the framework introduced by Andrés et al. (2004) and Marzo et al. (2008). In particular, we reproduce segmentation in financial markets by introducing bonds of different maturities and bond adjustment costs non-zero at the steady-state. These costs constitute structural liquidity frictions among bonds of different maturities: agents are assumed to pay a cost whenever they trade bonds intertemporally. As a result, the model is able to generate a non-zero demand for bonds of different maturities, which become imperfect substitutes, due to different liquidity conditions. The main properties of the model are analyzed through both simulation and estimation exercises. The contribution of the paper is twofold. On one hand, the calibrated model is able to replicate the stylized facts regarding the yield curve and the term premium in the US over the period 1987:3-2011:3, without compromising its ability to match macro dynamics. On the other hand, the estimation, besides providing an empirical support to the theoretical setting, highlights the potentialities of the model to analyze the term premium in a microfounded macro framework. The results match very closely the behavior of actual yields, reflecting the recent activity of the Fed on longer maturity bonds.

KEYWORDS: term structure, DSGE models
JEL Classification: C5, E32, E37, E43, E44

*Department of Economics, University of Bologna

†Department of Economics, University of Bologna, 2, Piazza Scaravilli; Mail: massimiliano.marzo@unibo.it. Phone: +39-0512098019

‡We have benefited from conversations with Davide Raggi, Alessandro Saia and Paolo Zagaglia. We also thank for helpful comments participants at seminars at the Department of Economics of the University of Bologna, at the European University Institute of Florence, at the PhD Conference in Monetary and Financial Economics 2012 organized by the Centre for Global Finance of Bristol, at the 5th PhD Conference in Economics organized by the University of Athens, and at the 53rd Annual Conference of the Italian Economic Association. The usual disclaimer applies.

1 Introduction

It is well known that one of the main limitations of standard Dynamic Stochastic General Equilibrium (DSGE) models is their inability to generate sufficiently large and volatile term premia.[1] Therefore, it has become an urgent task to better analyze the effects of real and nominal shocks on the term structure, and vice versa. Standard DSGE models, which represent the workhorse macro models of central banks and academic institutions, often lack a realistic and comprehensive representation of the financial sector. In particular, since all assets are taken as perfect substitutes, term premia are ignored, and the expectations hypothesis generally holds. Trying to incorporate in a coherent manner the term structure of interest rates into full-fledged DSGE models represents nowadays one of the most challenging research areas in macroeconomics.

In order to obtain richer models for policy advice it is crucial to bring term structure elements into general equilibrium frameworks. The yield curve is indeed very informative about expectations of future dynamics regarding macroeconomic variables (such as inflation and interest rates) and risk. More specifically, a complete understanding of term structure dynamics within DSGE models could be particularly helpful for the conduct of monetary policy. This issue has been gaining momentum in the last decade, as many central banks faced zero-bound interest rate challenges, or simply tried to react to unexpected or undesired changes of long term interest rates.

Recently, a macro-finance literature has been growing with the attempt to analyze how macro factors and the yield curve interact. Some works in this direction are due to Kozicki and Tinsley (2001), Ang and Piazzesi (2003), Hördahl et al. (2006), Evans and Marshall (2007), and Yang (2008), in which the macro structure is modeled as exogenous to the yield curve.[2] Other studies (Dewachter and Lyrio, 2006; Diebold et al., 2006; Rudebusch and Wu, 2007, 2008) are able to identify a bidirectional feedback between term structure factors and macro variables. The advantage of taking this joint perspective is twofold. On one hand, it is possible to observe how movements in the yield curve are affected by macroeconomic shocks. On the other hand, since the yield curve is a good predictor of future dynamics of the economy, these expectations contribute to the determination of current macroeconomic variables, although in a forward-looking setting. Thus, integrating term structure models with macro variables could substantially contribute to a better understanding of both financial and macroeconomic issues. Lastly, reduced-form macro models have been developed by Wu (2006), Hördahl et al. (2008) and Bekaert et al. (2010). However, it is clear that this kind of frameworks, either linking macro variables to some latent-factor finance structures or using reduced-form macro models, cannot adequately address some important questions regarding the complex interactions between macro variables and asset prices.

[1] This has been called in the literature *bond premium puzzle*, and is closely linked to the *equity premium puzzle* (Mehra and Prescott, 1985).

[2] This is the so-called dichotomous modeling approach (Rudebusch and Swanson, 2008). For an overview of this research area, see Diebold et al. (2005).

Another stream of the literature has focused on how to integrate yield curve dynamics into macro models with optimizing agents, such as DSGE models. Within these frameworks all variables obey a set of structural macro relations: for this reason, it is possible to give a more meaningful economic interpretation to the macro-finance connections. However, as explained by Rudebusch et al. (2007), standard DSGE models are not able to generate time-varying term premia. More specifically, the term premium is zero in first-order approximations, and constant in second-order approximations.

In order to address these drawbacks, the literature has explored four approaches. The first one tries to capture the variability of the term premium by using higher-order approximations or global nonlinear methods (Ravenna and Seppälä, 2006; Rudebusch et al., 2007; Rudebusch and Swanson, 2008, 2009) combined with long-memory habit formation in consumption (as suggested by Campbell and Cochrane (1999)) and labor market frictions (Uhlig, 2007). These models generally find a larger and more volatile term premium than standard models, but still without matching the dynamics shown by data (i.e. movements of the term premium are too small), or at the cost of distorting the model's ability to fit other macroeconomic variables, as reported by Rudebusch and Swanson (2008).

The second approach introduces Epstein and Zin (1989) recursive preferences to differentiate the intertemporal elasticity of substitution from the inverse of the risk aversion coefficient. In this context, Rudebusch and Swanson (2009), drawing on an endowment economy model with recursive preferences developed by Piazzesi and Schneider (2006), are able to generate substantial volatility in the term premium. In particular, the model produces a reasonably large and volatile term premium matching also basic macroeconomic moments. However, their results come at the cost of an unrealistically high risk aversion parameter. Other contributions using Epstein-Zin preferences are due to van Binsbergen et al. (2010) and Hsu (2011).

A third type of DSGE models is characterized by the presence of heterogeneous agents (Guvenen, 2009; De Graeve et al., 2010; Hsu, 2011). For instance, the model by De Graeve et al. (2010) is able to capture the role of heterogeneous capital market participation across agents (shareholders, bondholders and workers), generating realistic term premia and reasonable dynamics for the intra- and intertemporal allocation decisions.

Other efforts to explain asset prices in macro models have been pursued by the so-called *rare macroeconomic disasters* literature, according to which asset returns volatility can be explained by incorporating disaster risk, in the form of a probability that a disaster will happen in the future (Gourio, 2009; Barro and Ursua, 2011).

Despite these recent substantial improvements, Rudebusch (2010, p.40) himself admits that "the DSGE model financial sector remains far too rudimentary in terms of financial frictions and intermediation." More importantly, there are still theoretical uncertainties among economists about the appropriate model specification to analyze the term premium within a DSGE framework (Rudebusch et al., 2007).

This paper adopts and extends the DSGE framework proposed by Marzo et al. (2008), which was one of the first studies that endogenizes bond yields of different maturities.

In particular, our tractable model reproduces segmentation in financial markets by introducing bonds of different maturities and portfolio adjustment frictions. Transaction costs can be considered either as proxies for the liquidity of an asset, or simply costs associated to managing portfolios. Alternatively, the economic motivation for the inclusion of portfolio adjustment frictions may originate from the *preferred habitat theory*, whereby households have a preference for holding bonds of different maturity (Vayanos and Vila, 2009). These frictions generate a certain degree of stickiness in the timing of reallocation of bond holdings. As a result, the model is characterized by a non-zero demand for bonds of different maturities at each point in time, making assets imperfect substitutes. Our framework closely follows the message of Tobin (1969, 1982) about imperfect asset substitutability, whose portfolio approach has been first employed in a dynamic optimizing model by Andrés et al. (2004). With the model at hands, it is possible to analyze the dynamics of yield spreads and term premia in a general equilibrium setting. Moreover, the model features two feedback channels from the term structure to the macroeconomy that work, respectively, through the money demand and the resource constraint.

The main operational advantage emerging from this setting is given by its ability to generate time-varying term premia, without recurring to higher order approximation instead of the simple first-order log-linearized solution.

The novelties of this paper with respect to Marzo et al. (2008)'s contribution are basically three. First of all, we allow for a secondary market for bond trading, as proposed by Ljungqvist and Sargent (2004). Second, open market operations by the central bank are explicitly modeled, allowing the quantity of bonds of different maturities to move in response to shocks. Third, a deeper analysis of the term premium dynamics is conducted.

The results highlighted in this paper are important along two dimensions, and differ substantially from the original model by Marzo et al. (2008). On the one hand, the calibrated model is able to replicate stunningly well the stylized facts regarding the yield curve in the US over the period 1987:3-2011:3. More specifically, the moments of the simulated data match very closely those of the US yield curve. Moreover, the impulse response functions show that term premia react to shocks consistently with what is described in the literature. Finally, the model is able to generate a realistically high term premium while simultaneously matching the main macro dynamics, a fact that goes in the direction of solving the *bond premium puzzle*. The model is tested against data by using both calibration and Bayesian estimation methods. In particular, the estimation procedure highlights the full potential of the model in analyzing the term premium within a microfounded macro framework: the estimated term premium generated by the model is very similar to that obtained by Kim and Wright (2005), both in terms of pattern and volatility.

The model presented in this paper points to further avenues for future research, like, for example, an analysis of the recent waves of Quantitative Easing policies carried out by central banks, and the study of the strategic asset allocation implications.

The paper is structured as follows. Section 2 presents the model. The results from the calibrated model are discussed in Section 3, whereas Section 4 is devoted to the results from the estimation. Section 5 concludes.

2 The Model

A representative agent populates the economy and supply labor inputs. Monopolistically competitive firms hire labor and capital to produce differentiated goods. The government conducts fiscal and monetary policy.

2.1 The Household Sector

There is a continuum of identical and infinitely-lived households. Households' preferences are defined over consumption C_t, real money balances $\frac{M_t}{P_t}$ and labor effort L_t, and are described by the infinite stream of utility:

$$U_t = \sum_{t=0}^{\infty} \beta^t \nu_t^{PR} u\left(C_t, \frac{M_t}{P_t}, L_t\right) \tag{1}$$

where β is the intertemporal discount factor, and ν_t^{PR} is a preference shock that follows an AR(1) process:

$$\log \nu_t^{PR} = \phi_{PR} \log \nu_{t-1}^{PR} + \varepsilon_t^{PR} \tag{2}$$

where ε_t^p is an i.i.d. shock with zero mean and standard deviation σ_{PR}.
The instantaneous utility function $u\left(C_t, \frac{M_t}{P_t}, L_t\right)$ is given by:

$$u\left(C_t, \frac{M_t}{P_t}, L_t\right) = \frac{(C_t - \gamma C_{t-1})^{1-\frac{1}{\sigma}}}{1-\frac{1}{\sigma}} + \frac{1}{1-\chi}\left(\frac{M_t}{P_t}\right)^{1-\chi} - \frac{\Psi}{1+1/\psi} L_t^{1+1/\psi} \tag{3}$$

where σ is the elasticity of intertemporal substitution, γ measures the importance of consumption habits, χ is the elasticity of money demand, ψ is the Frisch elasticity of labor supply.

In this economy, each agent i can choose the composition of a basket of differentiated final goods. Preferences across varieties of goods have the standard constant elasticity of substitution (CES) form à la Dixit and Stiglitz (1977):

$$C_t = \left[\int_0^1 C_t(j)^{\frac{\theta_t - 1}{\theta_t}} dj\right]^{\frac{\theta_t}{\theta_t - 1}} \tag{4}$$

where C_t is the aggregate consumption index of all the differentiated final goods produced in the economy under monopolistic competition. There are j-th varieties of final goods ($j \in [0,1]$), and θ_t is a time-varying elasticity of substitution between different final goods varieties ($\theta_t > 1$).

Each agent is subject to the following budget constraint, which incorporates the secondary market for bond trading as in Ljungqvist and Sargent (2004):

$$\frac{B_t}{P_t R_t} + \frac{B_{S,t}}{P_t R_{S,t}}(1 + AC_t^S) + \frac{B_{M,t}}{P_t R_{M,t}}(1 + AC_t^M) + \frac{B_{L,t}}{P_t R_{L,t}}(1 + AC_t^L) + \frac{M_t}{P_t}(1 + AC_t^B) +$$
$$+ I_t(1 + AC_t^I) = \frac{B_{t-1}}{P_t} + \frac{B_{S,t-1}}{P_t R_t} + \frac{B_{M,t-1}}{P_t R_t} + \frac{B_{L,t-1}}{P_t R_t} + \frac{M_{t-1}}{P_t} + \frac{W_t}{P_t} L_t + q_t K_t - C_t - T_t + \Omega_t \tag{5}$$

Thus, agents allocate their wealth among money holding M_t, accumulation of capital K_t, which is rented to firms at the rental rate q_t, and holding of four types of zero-coupon government bonds (B_t, $B_{S,t}$, $B_{M,t}$, $B_{L,t}$), which are purchased by households at their nominal price. Agents receive rental income $q_t K_t$, where K_t is capital, wage income $w_t L_t$, where w_t is real wage, and a share of firms' profits Ω_t. They also pay a real lump-sum tax T_t; I_t is investment, and P_t is the aggregate price level. Firms face quadratic adjustment costs of investment as in Kim (2000):

$$AC_t^I = \frac{\phi_K}{2}\left(\frac{I_t}{K_t}\right)^2 \tag{6}$$

The law of motion of capital stock is expressed in the following standard way:

$$K_{t+1} = I_t + (1 - \delta) K_t \tag{7}$$

where δ represents the depreciation rate of capital stock.

The different zero-coupon government bonds are defined as money-market bonds B_t, short-term bonds $B_{S,t}$, medium-term bonds $B_{M,t}$, and long-term bonds $B_{L,t}$, whose yields are given, respectively, by R_t, $R_{S,t}$, $R_{M,t}$, and $R_{L,t}$. The left-hand side of the budget constraint follows the usual formulation with bonds priced at their interest rates, since at time t, the return $R_{\imath,t}$ is known with certainty and is risk-free from the viewpoint of agents. However, the right-hand side of (5) incorporates the secondary market for bond trading: bonds of different maturities are priced at the money-market rate. Even though these bonds represent sure claims for future consumption, they are subject to price risk prior to maturity. At time $t-1$, an agent who buys longer-maturity bonds and plans to sell them next period would be uncertain about the gains, since R_t is not known at time $t-1$. As stressed by Ljungqvist and Sargent (2004), the price R_t follows from a simple arbitrage argument, since, in period t, these bonds represent identical sure claims to consumption goods at the time of the end of the maturity as newly issued one-period bonds in period t.

As already mentioned, segmentation in financial markets is obtained by introducing portfolio adjustment frictions, representing impediments to the arbitrage behavior of agents that would equalize asset returns. First of all, we propose bond-adjustment costs (Marzo et al., 2008; Zagaglia, 2013), assuming that intertemporal bond trading is costly to each agent. Costs of bond adjustment are quadratic and are defined as follows:

$$AC_t^{\imath} = \left[\frac{\phi_{\imath}}{2}\left(\frac{B_{\imath,t}}{B_{\imath,t-1}}\right)^2\right] Y_t \tag{8}$$

where $\imath = S, M, L$. Costs defined by (8) are paid in terms of output, and are non-zero at the steady-state, generating a non-zero demand for bonds of different maturities in the long-run. The rationale behind the presence of transaction costs as in (8) is firstly related with the theory of preferred habitat, according to which agents have preferences over bond of different maturities (Vayanos and Vila, 2009). Under this view, transaction costs represent the inertial behavior of the investor located at each maturity. Moreover, these costs are proxies for the shares of resources devoted to covering information costs, or the costs of managing bond portfolios. As stressed by Marzo et al. (2008), the magnitude of the adjustment costs $\phi_{\imath}$ at the steady-state is different across maturities, as they reflect different opportunity costs of bonds. In particular, as long as $R_S < R_M < R_L$ (an upward sloping yield curve), we have $\phi_S < \phi_M < \phi_L$.
The bond adjustment costs proposed in (8) represent another crucial innovative point of the present paper, in contrast with the existing literature, where portfolio reallocation among bonds are assumed to be zero at the steady-state. This is what generates differential yields among bonds, emerging from structural liquidity conditions characterizing the market of bonds having different maturities.

Moreover, we add money-bond transaction costs following Andrés et al. (2004), given by:

$$AC_t^B = \left[\frac{v_S}{2}\left(\frac{M_t}{B_{S,t}}\kappa_S - 1\right)^2 + \frac{v_M}{2}\left(\frac{M_t}{B_{M,t}}\kappa_M - 1\right)^2 + \frac{v_L}{2}\left(\frac{M_t}{B_{L,t}}\kappa_L - 1\right)^2\right] Y_t \tag{9}$$

where $\kappa_{\imath} = b_{\imath}/m$ ($\imath = S, M, L$), i.e. the ratio between bond holdings and money in the steady-state. Thus, In other words, agents are assumed to pay a cost whenever their asset allocation moves away from a preferred portfolio composition. Costs (9) are assumed to be zero at the steady-state ad they can be viewed as a rationalization of the liquidity premium, representing the attitude towards risk on behalf of representative agent. Longer is the maturity of a bond, the less liquid is considered the asset. These costs are set to be increasing with maturity ($v_S < v_M < v_L$). Another intuition behind the presence of costs under (9) can be that agents perceive longer-maturity assets as riskier, and therefore associated to a loss of liquidity in comparison with the same investment in shorter-term bonds. For this reason, as they purchase longer-term bonds, they hold additional money to compensate themselves for the loss of liquidity. Thus, agents self-impose a sort of “reserve requirements” on their longer-term investments (Andrés et al., 2004).

2.1.1 Optimality Conditions

Households maximize their lifetime utility stream (1), subjected to (3), (5), (6), (7), (8) and (9), together with a usual transversality condition on all bonds.

The first order conditions with respect to consumption, labor, money, money-market bonds, short-term bonds, medium-term bonds, long-term bonds, capital and investment, are respectively given by:

$$\nu_t^P (C_t - \gamma C_{t-1})^{-1/\sigma} - \nu_{t+1}^P \beta \gamma E_t (C_{t+1} - \gamma C_t)^{-1/\sigma} = \lambda_t \tag{10}$$

$$\nu_t^P \Psi L_t^{1/\psi} = \lambda_t \frac{W_t}{P_t} \tag{11}$$

$$\begin{aligned} \nu_t^P \left(\frac{M_t}{P_t}\right)^{-\chi} \frac{1}{P_t} + \beta E_t \frac{\lambda_{t+1}}{P_{t+1}} = \frac{\lambda_t}{P_t}\left[1 + AC_t^B\right] + \\ + \lambda_t \frac{M_t}{P_t}\left[v_S \kappa_S \left(\frac{M_t}{B_{S,t}}\kappa_S - 1\right)\frac{Y_t}{B_{S,t}} + v_M \kappa_M \left(\frac{M_t}{B_{M,t}}\kappa_M - 1\right)\frac{Y_t}{B_{M,t}} + v_L \kappa_L \left(\frac{M_t}{B_{L,t}}\kappa_L - 1\right)\frac{Y_t}{B_{L,t}}\right] \end{aligned} \tag{12}$$

$$\beta E_t \frac{\lambda_{t+1}}{P_{t+1}} = \frac{\lambda_t}{P_t R_t} \tag{13}$$

$$\begin{aligned} \beta E_t \frac{\lambda_{t+1}}{\pi_{t+1} R_{t+1}} + \beta \phi_S E_t \frac{\lambda_{t+1}}{R_{S.t+1}} \left(\frac{B_{S,t+1}/P_{t+1}}{B_{S,t}/P_t}\right)^3 Y_{t+1} = \\ = \frac{\lambda_t}{R_{S,t}}\left[1 + \frac{3}{2}\phi_S \left(\frac{B_{S,t}/P_t}{B_{S,t-1}/P_{t-1}}\right)^2 Y_t\right] - \lambda_t \left[\left(\frac{M_t}{B_{S,t}}\right)^2 \kappa_S v_S \left(\frac{M_t}{B_{S,t}}\kappa_S - 1\right) Y_t\right] \end{aligned} \tag{14}$$

$$\begin{aligned} \beta E_t \frac{\lambda_{t+1}}{\pi_{t+1} R_{t+1}} + \beta \phi_M E_t \frac{\lambda_{t+1}}{R_{M.t+1}} \left(\frac{B_{M,t+1}/P_{t+1}}{B_{M,t}/P_t}\right)^3 Y_{t+1} = \\ \frac{\lambda_t}{R_{M,t}}\left[1 + \frac{3}{2}\phi_S \left(\frac{B_{M,t}/P_t}{B_{M,t-1}/P_{t-1}}\right)^2 Y_t\right] - \lambda_t \left[\left(\frac{M_t}{B_{M,t}}\right)^2 \kappa_M v_M \left(\frac{M_t}{B_{M,t}}\kappa_M - 1\right) Y_t\right] \end{aligned} \tag{15}$$

$$\beta E_t \frac{\lambda_{t+1}}{\pi_{t+1} R_{t+1}} + \beta \phi_L E_t \frac{\lambda_{t+1}}{R_{L.t+1}} \left(\frac{B_{L,t+1}/P_{t+1}}{B_{L,t}/P_t} \right)^3 Y_{t+1} =$$
$$= \frac{\lambda_t}{R_{L,t}} \left[1 + \frac{3}{2} \phi_L \left(\frac{B_{L,t}/P_t}{B_{L,t-1}/P_{t-1}} \right)^2 Y_t \right] - \lambda_t \left[\left(\frac{M_t}{B_{L,t}} \right)^2 \kappa_L \upsilon_L \left(\frac{M_t}{B_{L,t}} \kappa_L - 1 \right) Y_t \right] \quad (16)$$

$$\beta(1-\delta) E_t \mu_{t+1} = \mu_t - \lambda_t \left(q_t + \phi_K \left(\frac{I_t}{K_t} \right)^3 \right) \quad (17)$$

$$\beta E_t \mu_{t+1} = \lambda_t \left(1 + \frac{3}{2} \phi_K \left(\frac{I_t}{K_t} \right)^2 \right) \quad (18)$$

where λ_t and μ_t are the Lagrange multipliers.

2.2 Firms

Each j-th firm produces and sells differentiated final goods in a monopolistically competitive market. The production function is a standard Cobb-Douglas with labor and capital:

$$Y_t = A_t K_t^{\alpha} {L_t}^{1-\alpha} - \Phi \quad (19)$$

where α is the share of capital used in production, and Φ is a fixed cost to ensure that profits are zero in the steady-state. A_t is technology and follows an AR(1) process:

$$\log \left(\frac{A_t}{A} \right) = \phi_A \log \left(\frac{A_{t-1}}{A} \right) + \varepsilon_t^A \quad (20)$$

where ε_t^A is an i.i.d. shock with zero mean and standard deviation σ_A.

Firms face quadratic price adjustment costs à la Rotemberg (1982), given by:

$$AC_t^P = \frac{\phi_P}{2} \left(\frac{P_t(i)}{P_{t-1}(i)} - \pi \right)^2 Y_t \quad (21)$$

Given the standard CES setting of equation (4), the demand function faced by each single firm j is:

$$Y_t(j) = \left[\frac{p_t(j)}{P_t} \right]^{-\theta_t} Y_t \Longrightarrow P_t(j) = \left[\frac{Y_t(j)}{Y_t} \right]^{-\frac{1}{\theta_t}} P_t \quad (22)$$

Thus, the demand function for each single good j is proportionally related to the general output level of the economy, and negatively to the price of good j. The elasticity of substitution of demand θ_t is time-varying around a mean θ:

$$\theta_t = \theta + \nu_t^M \tag{23}$$

where ν_t^M is a shock to price mark-up that follows an autoregressive process:

$$\log \nu_t^M = \phi_M \log \nu_{t-1}^M + \varepsilon_t^M \tag{24}$$

where ε_t^M is an exogenous shock with zero mean and standard deviation σ_M.

With the presence of quadratic price adjustment costs highlighted under (21), the maximization problem becomes fully dynamic: each firm maximizes the expectation of the discounted sum of profit flows, given the information at time 0:

$$\Pi_0(j) = E_0 \left[\sum_{t=0}^{\infty} \rho_t P_t \Pi_t(j) \right] \tag{25}$$

where ρ is the firms' discount factor.

Following Kim (2000), the profit function for each firm j is:

$$P_t \Pi_t(j) = P_t(j) Y_t(j) - P_t W_t L_t(j) - P_t q_t K_t(j) - P_t AC_t^P \tag{26}$$

Assuming that each agent in the economy has access to a complete market for contingent claims, we have that the discount factor of households and firms are set to be equal, as in Kim (2000):

$$E_t \frac{\rho_{t+1}}{\rho_t} = E_t \beta \frac{\lambda_{t+1}}{\lambda_t} \tag{27}$$

Therefore, the FOCs of the maximization problem with respect to labor and capital are given, respectively, by:

$$\frac{W_t}{P_t} = (1-\alpha) \left(\frac{Y_t + \Phi}{L_t} \right) \left(1 - \frac{1}{e_t^Y} \right) \tag{28}$$

$$q_t = \alpha \left(\frac{Y_t + \Phi}{K_t} \right) \left(1 - \frac{1}{e_t^Y} \right) \tag{29}$$

where e_t^Y is the output demand elasticity:

$$\frac{1}{e_t^Y} = \frac{1}{\theta_t} \left\{ 1 - \phi_P (\pi_t - \pi) \pi_t + \beta \phi_P E_t \left[\frac{\lambda_{t+1}}{\lambda_t} (\pi_{t+1} - \pi) \pi_{t+1}^2 \frac{Y_{t+1}}{Y_t} \right] \right\} \tag{30}$$

which measures the gross price markup over marginal cost. Given the above structure, it is immediate to check that the standard New-Keynesian aggregate supply curve obtains naturally after repeated substitution of the previous equations one into the other, after log-linearization around the non-stochastic steady state.

2.3 The Government Sector

The government constraint is given by:

$$\frac{B_t}{P_tR_t}+\frac{B_{S,t}}{P_tR_{S,t}}+\frac{B_{M,t}}{P_tR_{M,t}}+\frac{B_{L,t}}{P_tR_{L,t}}+\frac{M_t}{P_t}=\frac{B_{t-1}}{P_t}+\frac{B_{S,t-1}}{P_tR_t}+\frac{B_{M,t-1}}{P_tR_t}+\frac{B_{L,t-1}}{P_tR_t}+\frac{M_{t-1}}{P_t}+G_t-T_t \tag{31}$$

where G_t is government spending, for which we assume to follow an AR(1) process:

$$\log\left(\frac{G_t}{G}\right)=\phi_G\log\left(\frac{G_{t-1}}{G}\right)+\varepsilon_t^G \tag{32}$$

where ε_t^G is an i.i.d. shock with zero mean and standard deviation σ_G.

We introduce the following fiscal policy rule, where the total amount of tax collection is a function of the total government's liabilities, in order to prevent the emergence of inflation as a fiscal phenomenon, as suggested by Leeper (1991):

$$T_t=\psi_0+\psi_1\left[\frac{b_{t-1}}{\pi_t}-\frac{b}{\pi}\right]+\psi_2\left[\frac{b_{S,t-1}}{R_t\pi_t}-\frac{b_S}{R\pi}\right]+\psi_2\left[\frac{b_{M,t-1}}{R_t\pi_t}-\frac{b_M}{R\pi}\right]+\psi_2\left[\frac{b_{L,t-1}}{R_t\pi_t}-\frac{b_L}{R\pi}\right] \tag{33}$$

where ψ_0 is the steady-state level of T_t, and ψ_1 has been set to be equal for all bonds. Equation (33) tells us that the level of taxes react to deviations of the outstanding level of public debt from its steady-state level. In other words, taxes are not allowed to act independently from the stock of government liabilities outstanding in the economy.

The central bank sets money-market rate R_t, according to the following Taylor (1993) rule:

$$\log\left(\frac{R_t}{R}\right)=\alpha_R\log\left(\frac{R_{t-1}}{R}\right)+(1-\alpha_R)\left\{\log\left(\frac{\pi_t^*}{\pi}\right)+\alpha_\pi\left[\log\left(\frac{\pi_t}{\pi}\right)-\log\left(\frac{\pi_t^*}{\pi}\right)\right]+\alpha_Y\log\left(\frac{Y_t}{Y}\right)\right\}+\varepsilon_t^R \tag{34}$$

where α_R, α_π, α_Y indicate the response of R_t with respect to lagged R_t, inflation and output. The policy rate is determined by the deviation of inflation and output from steady-state with an interest rate smoothing component. Monetary policy shock ε_t^R is an i.i.d. with zero mean and standard deviation σ_R. π_t^* is a time-varying inflation target, as in Smets and Wouters (2003) and Zagaglia (2013):

$$\log\left(\frac{\pi_t^*}{\pi}\right)=\phi_\pi\log\left(\frac{\pi_{t-1}^*}{\pi}\right)+\varepsilon_t^\pi \tag{35}$$

where ε_t^π is an exogenous shock with zero mean and standard deviation σ_π.

Finally, instead of assuming a simple exogenous AR process for the supply of bonds, as in Marzo et al. (2008) and Zagaglia (2013), let us suppose that central bank carries out a kind of "passive" open market operations (OMOs): whenever money demand increases (decreases), the central bank intervenes by buying (selling) government bonds of different maturities, and increasing (destroying) base money:

$$\frac{M_t/P_t}{M_{t-1}/P_{t-1}} = \left(\frac{B_{\imath,t}/P_t}{B_{\imath,t-1}/P_{t-1}}\right)^{-\eta_\imath} \varepsilon_t^{B\imath} \tag{36}$$

where $\eta_\imath$ is the elasticity of money growth supply with respect to changes in bond holdings for $\imath = S, M, L$. The coefficient $\eta_\imath$ indicates the extent by which changes in bond supply is reflected into money growth rate. According to (36), in order to respond to changes in money demand, the central bank varies the quantity of money supply by exchanging bonds, consistently with the policy-rate objective. where $\varepsilon_t^{B\imath}$ are i.i.d. shocks with zero mean and standard deviation $\sigma_{B\imath}$. Employing and manipulating (12), (13), (14), (15), and (16), equation (36) becomes:

$$b_{\imath,t} = b_{\imath,t-1} + A_1 R_{\imath,t} + A_2 \lambda_t + \dots \tag{37}$$

where the A coefficients are convolutions of structural parameters. From (37) we can observe that bond quantities depend positively on the interest rate. Thus, bond quantities are indirectly demand-driven.

The model is completed by specifying the resource constraint of the economy:

$$Y_t = C_t + G_t + I_t(1 + AC_t^I) + AC_t^P + \frac{b_{S,t}}{R_{S,t}}(AC_t^S) + \frac{b_{M,t}}{R_{M,t}}(AC_t^M) + \frac{b_{L,t}}{R_{L,t}}(AC_t^L) + m_t(AC_t^B) \tag{38}$$

Total output is allocated to consumption, government spending, investment (comprehensive of capital adjustment costs), price adjustment costs, and a component related to bond adjustment costs and money transaction costs.

2.4 The Pricing Kernel

It is now worth showing the main features underlying the bond pricing kernel emerging from this model, in order to understand why the expectations hypothesis does not hold within this framework. Following Ljungqvist and Sargent (2004) and Marzo and Zagaglia (2011), and assuming the simplest case without adjustment or transaction costs, we can rewrite the FOCs of bond quantities as follows:

$$\beta E_t \frac{\lambda_{t+1}}{\pi_{t+1}} = \frac{\lambda_t}{R_t} \tag{39}$$

$$\beta E_t \frac{\lambda_{t+1}}{\pi_{t+1} R_{t+1}} = \frac{\lambda_t}{R_{i,t}} \tag{40}$$

where $i = S, M, L$. The standard pricing kernel (or stochastic discount factor) is given by:

$$M_{t+1} = R_t^{-1} = \beta E_t \frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} \tag{41}$$

By using Eq.(41) and the law of iterated expectations, we obtain the pricing of a two-period bond:

$$R_{2,t}^{-1} = \beta^2 E_t \frac{\lambda_{t+2}}{\lambda_t \pi_{t+1} \pi_{t+2}} \tag{42}$$

We can generalize (42) to the j-th-period bond to get:

$$R_{j,t}^{-1} = \beta^j E_t \frac{\lambda_{t+j}}{\lambda_{t+j-1}(\pi_{t+1} \dots \pi_{t+j})} \tag{43}$$

The standard approach to term structure of interest rates implies that long-term interest rates are determined by expected future short-term rates. This is the so-called *expectations hypothesis*, whereby $R_{2,t} = R_t E_t R_{1,t+1}$. Let us check whether this hypothesis holds in our case. Eq.(40) can be rewritten as follows:[3]

$$R_{i,t}^{-1} = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} \right] E_t R_{t+1}^{-1} + Cov_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}}, R_{t+1}^{-1} \right] \tag{44}$$

Using Eq.(39), we obtain:

$$R_{i,t}^{-1} = R_t^{-1} E_t R_{t+1}^{-1} + Cov_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}}, R_{t+1}^{-1} \right] \tag{45}$$

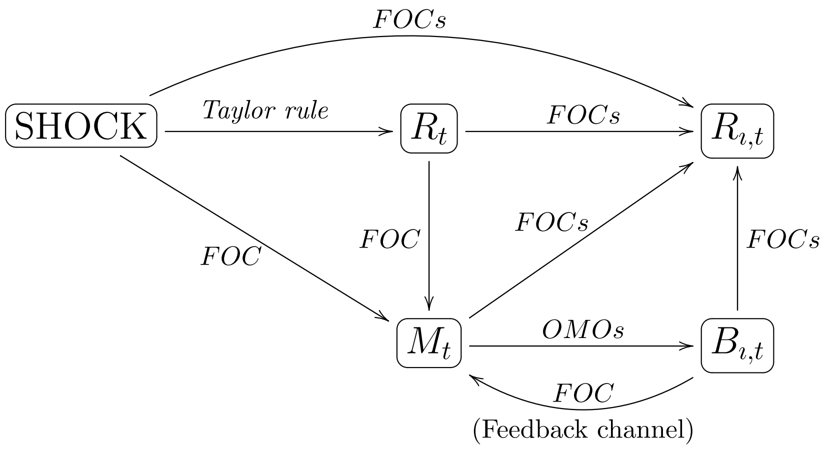
where the covariance term represents the term premium. Eq.(45) implies that the *Expectations Hypothesis*, (EH, henceforth) holds only when utility is linear in consumption, i.e. when $\frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} = 1$, leading the covariance term to disappear.

It is easy to verify that in the present setting the EH is not satisfied, since the utility is not linear in consumption. Moreover, there are also adjustment and transaction costs in the first order conditions of bonds of longer maturities (neglected in this analysis), that make the model characterized by a non-standard representation of the stochastic pricing equations. However, it is worth noting that what generates deviations from EH is the presence of the budget constraint with secondary markets, allowing for bond trading before their mature, while the portfolio adjustment frictions help to characterize the entire term structure by inserting wedges among the various rate of returns.

[3]Remember that $Cov(X, Y) = E[XY] - E[X]E[Y]$.

2.5 How Money, Bonds and Yields Interact

It is evident that the model presents non-trivial dynamics for what concerns the relationships between money, yields and quantity of bonds. This paragraph aims to shed light on these mechanisms. The interrelationships among money, bonds and returns are depicted in the following diagram. Notice, in particular, that, differently from what has been assumed by Marzo et al. (2008), there is an effective bidirectional feedback between money and bond quantities, due to the presence of open market operations.



Leaving aside the policy rate, determined by Taylor rule (34), and bond quantities of longer maturities, determined by open market operations (36), let us focus on the other variables of interest. Consider first a simplified log-linearized version of money demand equation:

$$\tilde{m}_t = B_1 E_t \tilde{c}_{t+1} - B_2 \tilde{c}_t + B_3 \tilde{c}_{t-1} - B_4 \tilde{R}_t + B_5 \tilde{b}_{S,t} + B_6 \tilde{b}_{M,t} + B_7 \tilde{b}_{L,t} \tag{46}$$

where the B coefficients are convolutions of structural parameters. Given the imperfect substitutability between money and bond holdings, money demand is positively affected by quantities of bonds at short, medium, and long maturities. This is due to the presence of the money-bond transaction costs. As previously stressed, households purchase longer-term assets and hold additional money to compensate for the potential loss of liquidity. Eq.(46) highlights one of the two feedback channels of the model from the term structure to the macroeconomy stressed by Marzo et al. (2008) and Zagaglia (2013), namely a money demand channel. The other feedback channel works through the resource constraint, as it is possible to see by looking at Eq.(38). In the latter case, bond transaction costs directly affect the spending decisions of agents.[4]

[4]It is worth to note that the present model lacks a channel through which aggregate demand depends directly on the prices of both short-term and longer-term maturity bonds, as in Harrison (2012) and Falagiarda (2013).

The log-linearized version of the first order conditions of bond holdings, from which yields of different maturities are derived, is given by:

$$\tilde{R}_{\imath,t} = C_1\tilde{\lambda}_t - C_2 E_t\tilde{\lambda}_{t+1} + C_3 E_t\tilde{\pi}_{t+1} - C_4 E_t\tilde{y}_{t+1} + C_5\tilde{y}_t + C_6 E_t\tilde{R}_{\imath,t+1} + C_7 E_t\tilde{R}_{t+1} - \\ - \underbrace{\upsilon_\imath C_8[\tilde{m}_t - \tilde{b}_{\imath,t}]}_{\text{Imperfect asset substitutability}} + \underbrace{\phi_\imath C_9\tilde{b}_{\imath,t} - \phi_\imath C_{10}\tilde{b}_{\imath,t-1} - \phi_\imath C_{11} E_t\tilde{b}_{\imath,t+1}}_{\text{Intertemporal stickiness}} \tag{47}$$

where $\imath = S, M, L$, and the C coefficients are convolutions of structural parameters. Thus, yields of longer maturities are determined also by two components generated by portfolio adjustment frictions, which characterize respectively the degree of imperfect asset substitutability and the degree of intertemporal stickiness of bond trading. In particular, Eq.(47) reveals that the long-term rate depends positively on long-term bond supply, as desired, and positively on money supply, because of the imperfect asset substitutability. In other words, an increase in the relative supply of the more illiquid asset will bid up the spread between the more illiquid asset and the more liquid asset.
It is immediate to check that transaction and adjustment costs parameters generate impediments to the arbitrage activity which would equalize returns. At the same time, the presence of transaction costs determines the extent of the influence of relative assets holdings on long-term rate. In (47), when $\phi_\imath = 0$, deviations from EH are smaller, and longer-term rates are not affected by changes in relative assets holdings.

3 The Results from the Calibrated Model

The model has been log-linearized around the non-stochastic steady-state, whose details are reported in the Appendix. We generate artificial time series of the variables, by simulating 1000 observations and discarding the first 500. In what follows we report the calibration strategy.

3.1 The Calibration

The benchmark model is calibrated to match US quarterly data over the period 1987:3-2011:3, the Greenspan-Bernanke era. Table 1 and Table 2 report, respectively, the steady-state values and the calibrated values of the core parameters. Some values have been chosen by following previous studies and are quite standard in the DSGE literature. In particular, the elasticity of substitution across goods θ is set to be equal to 6 (as Schmitt-Grohé and Uribe (2004)); habit formation parameter γ, is set to be equal to 0.7 (as in Smets and Wouters (2007)); the elasticity of intertemporal substitution σ, is 0.5, which implies a coefficient of relative risk aversion of 2; the depreciation rate of capital δ is calibrated to be 0.025 (as in Christiano et al. (2005) and Altig et al. (2011)): this value implies an annual rate of depreciation on capital equal to 10 percent.

Capital share in production function α is set to 0.36 (Christiano et al., 2005; Altig et al., 2011); parameter of price adjustment cost ϕ_P, is set to be calibrated to 100 (Ireland, 2004). The elasticity of real money balances χ is set equal to 7, as in Marzo et al. (2008); the Frisch elasticity ψ is set equal to 1 (Marzo et al. (2008)).

The parameters of the fiscal and monetary policy rules are mainly calibrated following Marzo et al. (2008), while the AR coefficients and the standard deviations of the shocks are set to $\phi_A = 0.95$, $\phi_G = \phi_M = 0.90$, $\sigma_A = 0.01$, $\sigma_R = 0.005$, $\sigma_G = 0.012$ (see, for example, Christiano and Eichenbaum, 1992; Kim, 2000; Andrés et al., 2004; Marzo et al., 2008; Altig et al., 2011; Zagaglia, 2013).

Transaction costs between money and bonds are considered as free parameters and are calibrated to match the empirical moments of the US yield curve, in the benchmark case. Their values are respectively set to be: $\upsilon_S = 0.0030$ (which means 0.3% of income), $\upsilon_M = 0.004$, and $\upsilon_L = 0.0041$. In the next paragraphs a sensitivity analysis on these parameters will be performed to test robustness of the results conditional to benchmark calibrated values.

For what concerns the parameters η_S, η_M and η_L, their calibrated values are obtained from data concerning the conduct of open market operations in the US. We rely therefore on various issues of the *Domestic Open Market Operations Report* prepared by the New York Fed, and we set these parameters to 2.5, 2.5, and 7, respectively. These values are indicative of the period prior to the financial crisis, during which holdings of government securities were skewed towards the shorter end of the maturity spectrum. In fact, it is well known that, from 2008, purchases of government securities were instead weighted towards longer term maturities. However, in the next section we will carry out some sensitivity analysis on these parameters, in order to show the mechanisms behind the OMOs formulation within this framework.

The steady-state value of some variables is obtained from the data, or following previous studies. Output is normalized to 1. The consumption-output ratio has been set to 0.57, and the taxes-output ratio to 0.1972 (Marzo et al., 2008). The ratio of market to non-market activities is set equal to 0.3. The ratio of total debt on GDP is calibrated to 0.45 (Schmitt-Grohé and Uribe, 2004; Marzo et al., 2008). The ratio of debt at different maturities to total debt is obtained from the *OECD Database*, using US series from 1995 to 2010 and calculating the average over this period. The steady-state values of the yields have been calculated from the *Federal Reserve Economic Data*.

Finally, values of remaining parameters and variables are computed using steady-state solutions, as shown in the Appendix.

3.2 The Benchmark Model

3.2.1 Moments of the Simulated Variables

It is useful to start by illustrating some stylized fact of the US term structure in recent years. Table 3 summarizes the main moments of US term structure over the period 1987:3-2011:3. We report standard deviations of yield spread and yields of four maturities (the

Federal Funds Rate, 3 months, 1 year, 5 years, and 10 years), and the correlation between the output gap (computed as a percentage deviation of real GDP from potential) and the yield spread. The statistics have been computed using *Federal Reserve Economic Data*. As expected, rates of shorter maturity are generally more volatile than those of longer maturities. Moreover, the yield spread is countercyclical.

Table 4 displays the analogous statistics of the simulated data generated by the model using the benchmark calibration.[5] Standard deviations of various maturities yields are extremely close to actual data, reported in Table 3. The same can be said for the volatility of yield spreads. The only exception is the policy rate, whose standard deviation is very low because we did not include any specific investment technology (like transaction costs) for bonds paying a return equal to the policy rate, as explained by Ljungqvist and Sargent (2004, p.377).

Furthermore, the contemporaneous correlation of the spread with the output gap is negative, as found in actual data over the sample considered. We also report the standard deviation of the generated term premium, as well as its contemporaneous correlation with the output gap. The term premium is found to be countercyclical: this negative relationship in real data is documented by Rudebusch et al. (2007). More importantly, it is worth noting that in comparison with standard DSGE models using higher order approximations, the standard deviation of the term premium emerging from our model is much higher and very close to the empirical one that is 0.752.[6]

Thus, it seems that the model in its benchmark calibrated version is able to generate moments that match stunningly well the US term structure features over the Greenspan-Bernanke period, and, at the same time, to reproduce a sufficiently and realistically large term premium.

3.2.2 Impulse Response Functions

Impulse response functions (IRFs) with respect to one standard deviation innovations to the three main shocks (technology, monetary policy and government spending) are shown in Figures 1-3.[7] A positive productivity shocks (Figure 1) leads to a decreasing response of inflation, which, in turn, causes a reduction in the monetary policy rate.

[5] The yield spread is simply computed by taking the difference between the long-term rate and the money-market rate. The term premium ξ_t is defined as follows:

$$R_{L,t} = \frac{1}{N}\sum_{j=0}^{N-1} E_t R_{S,t+j} + \xi_t$$

Thus, the term premium is the deviation of the long-term yield $R_{L,t}$ from the level consistent with the expectations hypothesis. Since we assume that the short-rate $R_{S,t}$ is the 3-month yield and the long-term rate $R_{L,t}$ is the 10-year rate, we have $N = 40$.

[6] We use the term premium estimated by Kim and Wright (2005), computed over the period 1990:4-2011:3.

[7] The IRFs regarding the other shocks, not reported here, are available upon request.

Moreover, the responses of the remaining yield rates are negative, due to the decreasing response in money-market rate. After the shock money demand increases, while the term premium falls, reaching a minimum of around 0.13%. The direction of the response of the term premium is consistent with what has been showed by Rudebusch et al. (2007) in a standard business cycle model with a third-order approximation. However, our model is able to generate a response substantially higher than that reported in Rudebusch et al. (2007). Finally, main macro variables dynamics are perfectly consistent with the patterns derived from a standard DSGE model.

Figure 2 plots the impulse responses to a contractionary monetary policy shock, which, not surprisingly, triggers a negative response of inflation and output. The increase in the policy rate drives money demand down, and yields of different maturities hike: the model does not display any liquidity puzzle. Moreover, on impact after the shock the term premium displays an increase: this is again consistent with Rudebusch et al. (2007). Previous considerations about the size of the response of the term premium and the dynamics of the macro variables apply for results displayed in Figure 2 as well.

A government spending shock (Figure 3) leads to an increase in output and inflation, crowding out consumption. As a result, money demand falls, driven by an increase in the policy rate. In line with Rudebusch et al. (2007), the term premium experiences an increase on impact.

Summing up, we have shown that the baseline version of the model is capable to match the main stylized fact about the US term structure without distorting the dynamics of the main macro variables. To our knowledge, this is the first DSGE model that, by endogenizing the term structure, is able to achieve this goal. In particular, while the direction of the response of the term premium to the shocks is consistent with what previously found in the DSGE literature, its magnitude is much higher. Next paragraphs are devoted to sensitivity analysis, where we will show how the term structure dynamics vary after changing key model parameters.

3.3 Sensitivity Analysis

The goal of the next two paragraphs is to gain intuition about some of the mechanisms at work in the model. In particular, we analyze what happens when changing, first, the money transaction costs, and then the parameters relative to the open market operations.

3.3.1 The Role of Money Transaction Costs

Figure 4 shows the impulse response functions of a technology shock for different values of the transaction costs parameters, while simulated moments are reported in Table 5. It is worth remembering that, in this framework, variations in the transaction costs reflect variations in the liquidity of the asset: the higher the transaction costs, the higher the liquidity premium associated with that kind of asset. It is evident from Figure 4 that the responsiveness of each yield increases when its own transaction cost increases. Table 5 shows that even yield volatility is larger, when the value of the transaction costs is higher. The intuition is simple. When transaction cost is lower (higher), the bond becomes more (less) liquid, and, therefore, the propensity of agents to reallocate income between money and bonds is higher (lower), since the degree of substitutability between money and bonds increases (decreases). As a result, the responsiveness to shocks of the bond's price and yield decreases (increases), as shocks can be better absorbed in liquid markets (i.e. the stress over yields is lower in liquid markets). Finally, a lower (higher) responsiveness of yields reflects, in turn, a lower (higher) degree of volatility of the simulated yields. In other words, deviations of prices and yields from the steady-state are less pronounced in a liquid market, in which it is relatively easy to trade asset. The price impact to a specific shock is lower.

Finally, given existing parameter values, feedback effects from the term structure to the macroeconomy, highlighted in paragraph 2.5, although present, are negligible (Figure 4).

3.3.2 The Role of Open Market Operations

Impulse response functions to a productivity shock and the moments of the simulated variables when varying the parameters of the open market operations $\eta_\imath$, for $\imath = S, M, L$, are respectively displayed in Figure 5 and Table 6. They indicate that the higher the parameter of Open Market Operations for a specific bond, the lower is the responsiveness and the volatility of its own yield. The explanation is straightforward. The higher (lower) is the parameter, the lower (higher) is the quantity of bonds of that type that the central bank is buying or selling on the markets after a variation of the money demand. As a result, also the volatility of prices and yields of that specific asset turns out to be lower (higher). Also in this case, the feedback effects are not fully appreciable.

Lastly, it is worth briefly emphasizing the potentialities of this model of analyzing *unconventional* tools for monetary policy, such as Quantitative Easing policies, which have become very popular in the recent years, given that in many countries short-term interest rates have been very close to the zero lower bound.[8] Indeed, within this framework, it would be possible to study the response of yields of different maturities to longer-term assets purchases by the central bank. This issue goes beyond the scope of the present paper, and is the focus of another work (Falagiarda, 2013).

3.4 Yield Spread Decomposition

We decompose the yield spread into an expectations component and a term premium, in order to analyze the relative contribution of each component to movements of the yield

[8]See, for example, Gagnon et al. (2010) and Krishnamurthy and Vissing-Jorgensen (2011).

spread. This decomposition takes the following form:

$$\underbrace{R_{L,t} - R_{S,t}}_{\text{Yield spread}} = \underbrace{\left[\frac{1}{N}\sum_{j=0}^{N-1} E_t R_{S,t+j} - R_{S,t}\right]}_{\text{Expectations component}} + \underbrace{\left[R_{L,t} - \frac{1}{N}\sum_{j=0}^{N-1} E_t R_{S,t+j}\right]}_{\text{Term premium}} \tag{48}$$

with $N = 40$. Figure 6 displays the relative contribution of each component concurring to determine yield spread variations, using simulated data. As also proved analytically in paragraph 2.4, the model generates substantial deviations from the EH. In fact, with baseline calibration, the expectations-related component accounts on average for more than 54% of yield spread changes (Figure 6). By increasing transaction costs on long-term bonds, the contribution of the term premium becomes predominant. At the contrary, an increase in transaction costs on short-term bonds leads the expectations component to take a larger share, since the wedge between short-term and long-term rate becomes smaller.[9]

4 The Results from the Estimated Model

Once the model has proved to do a good job in its calibrated version, in terms of both term structure moments and macro dynamics, a natural step forward is to carry out a more direct link of theory with data by explicitly estimating the model. The estimation is conducted on US data at a quarterly frequency over the period considered before (1987:3-2011:3).

The goal of the estimation exercise is twofold. First, we check whether the assumptions about the parameters used in the calibrated version are empirically plausible, at least as a first approximation. Obviously, our main focus is on the parameters regarding money transaction costs and open market operations. Second, the time series of the estimated term premium is compared with that obtained by Kim and Wright (2005), who use an affine term structure model to estimate term premium movements.

4.1 The Estimation Technique

Estimation is performed using Bayesian techniques, which have become very popular in the DSGE literature in the last decade, as carefully explained in Fernández-Villaverde (2010). Once the model has been log-linearized, we can write it in a state space representation, where the transition equation is:

$$S_t = f(S_{t-1}, W_t; \Theta) \tag{49}$$

[9] The graphs are available upon request.

where S_t is the vector of states, W_t is the vector of innovations, and Θ is the vector of structural parameters.

The measurement equation is:

$$Y_t = g(Y_{t-1}, Z_t; \Theta) \tag{50}$$

where Y_t are the observables and Z_t the measurement errors to the observables.

Given our data $Y^T \equiv \{Y_t\}_{t=1}^T$, the general expression of the likelihood function of the model is:

$$\mathcal{L}\left(\Theta|Y^T\right) = \prod_{t=1}^{T} p\left(Y_t|Y^{T-1}, \Theta\right) \tag{51}$$

The likelihood function is evaluated through the Kalman filter.[10] According to Bayes' theorem, the posterior distribution of the parameters is given by:

$$\pi\left(\Theta|Y^T\right) = \frac{p(Y^T|\Theta)\pi(\Theta)}{\int p(Y^T|\Theta)\pi(\Theta)d\Theta} \tag{52}$$

Using a Random Walk Metropolis-Hastings algorithm, as described by Chib and Greenberg (1995), An and Schorfheide (2007), and Fernández-Villaverde (2010), we obtain an empirical approximation of the posterior density function of the model, ready to perform inference.

The chosen observables are output, inflation, consumption, money, short term rate, medium-term rate, and long-term rate. Quarterly data on real GDP, GDP deflator, real consumption expenditure, money base M0, and yields (respectively, 3-month, 1-year, and 10-year yields - constant-maturity interest rates, in percent per year) covering the period 1987:3-2011:3 are employed. They are obtained from the *Federal Reserve Economic Data* database. We calculate log-differences of each series, with the exception of interest rates. The dataset is then detrended using a linear trend.

4.2 Prior Distribution of the Parameters

Some parameters are not estimated, since they are either obtained through the steady-state solution or usually treated as fixed in the literature (such as the coefficient of intertemporal substitution β). The remaining parameters are estimated, and their prior distribution is shown in the second column of Table 7, chosen consistently with the calibration of previous section, or following previous contributions in the literature (Smets and Wouters, 2003; Del Negro et al., 2007; Smets and Wouters, 2007; Zagaglia, 2013).

[10] For more details, see Canova (2007).

4.3 The Results

The posterior mean estimates of parameters are reported in the third column of Table 7.[11] The estimated posterior mean of almost all the parameters estimates is quite close to the prior mean, with the exception of the standard error and the stochastic process of government spending shock, which displays a higher standard error, and a lower persistence. Other divergences between priors and posteriors are physiological, as documented in the literature.

Looking at the estimates of *free parameters* - those regarding money adjustment costs and open market operations - it turns out that the mean of the posterior distribution generally departs from the mean of the prior assumptions, and the estimates generally respect the ordering of their calibrated value, except for the parameter of medium-term bonds adjustment costs, slightly higher than that of long-term bond. This is probably due to the fact that medium term bonds are usually less actively traded than short- and long-term bonds. Moreover, the estimates confirm that OMOs are more skewed towards short and medium-term securities. These results seem to provide a strong empirical support to our previous calibration and to the whole theoretical framework. In addition, concerns of weak identification, which usually arise for these types of parameters (Chen et al., 2012; Falagiarda, 2013), do not seem justified, i.e. the data are informative for identifying these parameters.

On the other hand, the main goal of the estimation carried out in this section is to show how powerful the present model is for studying term premium dynamics. We showed that this model is able to generate an endogenous term premium. Figure 7 compares the series of the estimated term premium with that obtained by Kim and Wright (2005), who employ an affine term structure model. It should be remembered that we are dealing with deviations from the steady-state and our time series have already been detrended: to facilitate comparisons, the term premium by Kim and Wright (2005) has also been detrended. From Figure 7 we observe a considerable similarity in the volatility of the two series. The slightly smaller volatility of our estimated term premium may be ascribed to the absence of inflation risk in the model, which has been recenlty found as an important determinant of term premium variations (Wright, 2011). Secondly, the two term premia follow very similar patterns, as proved by the high correlation coefficient between them, given by 0.638.

As a last exercise, we carry out the estimation over two sub-periods, 1987:3-1998:1 and 1998:2-2011:3. Figure 8 and 9 report posterior impulse response functions of term structure variables to technology and monetary policy shocks over the full sample period and the two sub-periods.[12] They represent the mean of a series of impulse response

[11]Estimates are obtained using two blocks of 100,000 replications each, of which the first 45 percent have been discarded. The convergence diagnostic tests indicate that the Markov chains converge. Moreover, the Bayesian IRFs reflect the dynamics highlighted in the calibrated model. For reasons of space, both set of graphs have not been reported here, but are available upon request.

[12]The confidence intervals have not been reported for the sake of clarity. All the responses are nevertheless statistically significant at least at 5% level.

functions obtained by drawing from the parameter posteriors. The responses have been rescaled in order to capture a 1% shock. First of all, it should be noted that the direction of the responses are consistent with the predictions obtained from the theoretical model. More importantly, it is possible to observe that the two sub-periods are characterized by different degrees of responsiveness of yields of different maturity. In fact, during the first sub-period, yields' reaction to shocks is smaller and less persistent in comparison with that relative to the second sub-period. The reason is likely to be found in the fact that in the recent years financial markets have been substantially more turbulent. The bubbles characterizing the early 2000s and the recent Great Recession are just the most celebrated examples. Moreover, the pattern of the model relatively to the more recent sample period (1998:2-2011:3) shows a clear effect of the more active role of central banks over longer maturities, if compared with previous periods.

In conclusion, through this estimation exercise, we have shown that this approach, by considering the term premium as an endogenous variable, allows yield curve dynamics to be analyzed in a much deeper way than standard DSGE models. In particular, the estimated term premium is realistically large and follows very closely the pattern of that estimated by Kim and Wright (2005) using a finance model.

5 Concluding Remarks

In this paper, we introduce a new way of modeling the term structure within a DSGE framework. In particular, by introducing portfolio adjustment frictions on bond trading, it is possible to generate segmented financial markets, in which assets of different maturities are imperfect substitutes. This allows for a full endogenization of a time-varying term premium.

The calibrated model is able to match both US term structure moments over the period 1987:3-2011:3 and the main macro dynamics. Moreover, it generates a sufficiently large term premium without using higher order approximations, which reacts to shocks consistently with what found in previous studies.

The estimation exercise performed in Section 4 provides a strong empirical support to this theoretical framework. In particular, the estimates of the free parameters of the model are in line with their calibrated values, and the responses of yields of different maturity consistent with theoretical predictions. Moreover, the estimated term premium generated by the model is very similar to that obtained by Kim and Wright (2005), both in terms of pattern and volatility.

All in all, the most important contribution of this paper is to provide a new setting, through which the term premium can be incorporated into a microfounded macro framework with optimizing agents. Further work is needed to better evaluate the role of money, and to identify movements and determinants of the yield curve. In addition, the model proposed in this paper points to further avenues for future research, such as the introduction of financial intermediaries and different categories of assets, and the analysis of the strategic asset allocation implications of this framework. It would also be important to adopt a more effective feedback mechanism from the term structure to the macroeconomy, such that employed by Harrison (2012), in which, in a similar model, aggregate demand depends directly on interest rates of bonds of different maturities. Moreover, it would be interesting to adapt and use this framework to study the recent waves of Quantitative Easing policies carried out by central banks in the US and the UK.

Appendix. The Steady-State

$$\lambda = (1-\beta\gamma)[C(1-\gamma)]^{-\frac{1}{\sigma}} \tag{53}$$

$$\beta = \frac{\pi}{R} \tag{54}$$

$$m^{-\chi} = \lambda\left(1-\frac{1}{R}\right) \tag{55}$$

$$\Psi = \frac{\lambda}{L^{1/\psi}w} \tag{56}$$

$$\beta\frac{1}{\pi R} + \beta\phi_i\frac{1}{R_i}Y = \frac{1}{R_i}\left[1+\frac{3}{2}\phi_i Y\right] \tag{57}$$

$$\phi_i = \frac{\frac{\beta R_i}{\pi R}-1}{Y\left(\frac{3}{2}-\beta\right)} \tag{58}$$

$$K = \frac{I}{\delta} \tag{59}$$

$$\frac{G}{Y} = 1-\frac{C}{Y} - I_t(1+AC_t^I) - \frac{\phi_S}{2}\frac{b_S}{R_S} - \frac{\phi_M}{2}\frac{b_M}{R_M} - \frac{\phi_L}{2}\frac{b_L}{R_L} \tag{60}$$

$$w = (1-\alpha)\left(\frac{Y+\Phi}{L}\right)\left(1-\frac{1}{e^Y}\right) \tag{61}$$

$$q = \alpha\left(\frac{Y+\Phi}{K}\right)\left(1-\frac{1}{e^Y}\right) \tag{62}$$

$$\Phi = \left[1-\alpha\left(1-\frac{1}{\theta}\right)\right]AK^\alpha L^{1-\alpha} \Longrightarrow \frac{\Phi}{Y+\Phi} = \left[1-\alpha\left(1-\frac{1}{\theta}\right)\right] \tag{63}$$

$$e^{Y} = \theta \tag{64}$$

Combining equations (17) and (18), we have the following formula, from which we can derive ϕ_K:

$$\beta E_t \frac{\lambda_{t+1}}{\lambda_t} \left\{ (1-\delta) \left[1 + \frac{3}{2} \phi_K \left(\frac{I_{t+1}}{K_{t+1}} \right)^2 \right] + Q_{t+1} + \phi_K \left(\frac{I_{t+1}}{K_{t+1}} \right)^3 \right\} = 1 + \frac{3}{2} \phi_K \left(\frac{I_t}{K_t} \right)^2 \tag{65}$$

References

Altig, D., Christiano, L. J., Eichenbaum, M., and Lind, J. (2011). Firm-specific capital, nominal rigidities and the business cycle. *Review of Economic Dynamics*, 14(2):225–247.

An, S. and Schorfheide, F. (2007). Bayesian analysis of DSGE models. *Econometric Reviews*, 26(2-4):113–172.

Andrés, J., López-Salido, J. D., and Nelson, E. (2004). Tobin's imperfect asset substitution in optimizing general equilibrium. *Journal of Money, Credit and Banking*, 36(4):665–690.

Ang, A. and Piazzesi, M. (2003). A no-arbitrage vector autoregression of term structure dynamics with macroeconomic and latent variables. *Journal of Monetary Economics*, 50(4):745–787.

Barro, R. J. and Ursua, J. F. (2011). Rare macroeconomic disasters. Working Paper 17328, National Bureau of Economic Research.

Bekaert, G., Cho, S., and Moreno, A. (2010). New keynesian macroeconomics and the term structure. *Journal of Money, Credit and Banking*, 42(1):33–62.

Campbell, J. Y. and Cochrane, J. H. (1999). By force of habit: A consumption-based explanation of aggregate stock market behavior. *Journal of Political Economy*, 107(2):205–251.

Canova, F. (2007). *Methods for applied macroeconomic research.* Princeton University Press.

Chen, H., Cúrdia, V., and Ferrero, A. (2012). The macroeconomic effects of large-scale asset purchase programmes. *Economic Journal*, 122(564):F289–F315.

Chib, S. and Greenberg, E. (1995). Understanding the Metropolis-Hastings algorithm. *The American Statistician*, 49(4):pp. 327–335.

Christiano, L. J. and Eichenbaum, M. (1992). Current real-business-cycle theories and aggregate labor-market fluctuations. *American Economic Review*, 82(3):430–450.

Christiano, L. J., Eichenbaum, M., and Evans, C. L. (2005). Nominal rigidities and the dynamic effects of a shock to monetary policy. *Journal of Political Economy*, 119(1):1–45.

De Graeve, F., Dossche, M., Emiris, M., Sneessens, H., and Wouters, R. (2010). Risk premiums and macroeconomic dynamics in a heterogeneous agent model. *Journal of Economic Dynamics and Control*, 34(9):1680–1699.

Del Negro, M., Schorfheide, F., Smets, F., and Wouters, R. (2007). On the fit of new Keynesian models. *Journal of Business and Economic Statistics*, 25(2):123–143.

Dewachter, H. and Lyrio, M. (2006). Macro factors and the term structure of interest rates. *Journal of Money, Credit and Banking*, 38(1):119–140.

Diebold, F. X., Piazzesi, M., and Rudebusch, G. D. (2005). Modeling bond yields in finance and macroeconomics. *The American Economic Review*, 95(2):415–420.

Diebold, F. X., Rudebusch, G. D., and Aruoba, S. B. (2006). The macroeconomy and the yield curve: a dynamic latent factor approach. *Journal of Econometrics*, 131(1-2):309–338.

Dixit, A. K. and Stiglitz, J. E. (1977). Monopolistic competition and optimum product diversity. *American Economic Review*, 67(3):297–308.

Epstein, L. G. and Zin, S. E. (1989). Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework. *Econometrica*, 57(4):937–969.

Evans, C. L. and Marshall, D. A. (2007). Economic determinants of the nominal treasury yield curve. *Journal of Monetary Economics*, 54(7):1986–2003.

Falagiarda, M. (2013). Evaluating Quantitative Easing: A DSGE approach. MPRA Paper 49457, University Library of Munich.

Fernández-Villaverde, J. (2010). The econometrics of DSGE models. *SERIEs: Journal of the Spanish Economic Association*, 1:3–49.

Gagnon, J., Raskin, M., Remache, J., and Sack, B. (2010). Large-scale asset purchases by the Federal Reserve: Did they work? Staff Reports 441, Federal Reserve Bank of New York.

Gourio, F. (2009). Disasters risk and business cycles. Working Paper 15399, National Bureau of Economic Research.

Guvenen, F. (2009). A parsimonious macroeconomic model for asset pricing. *Econometrica*, 77(6):1711–1750.

Harrison, R. (2012). Asset purchase policy at the effective lower bound for interest rates. Bank of England working papers 444, Bank of England.

Hördahl, P., Tristani, O., and Vestin, D. (2006). A joint econometric model of macroeconomic and term-structure dynamics. *Journal of Econometrics*, 131(1-2):405 – 444.

Hördahl, P., Tristani, O., and Vestin, D. (2008). The yield curve and macroeconomic dynamics. *Economic Journal*, 118(533):1937–1970.

Hsu, A. (2011). Does fiscal policy uncertainty matter for bond risk premia? Unpublished manuscript.

Ireland, P. N. (2004). Money's role in the monetary business cycle. *Journal of Money, Credit and Banking*, 36(6):969–83.

Kim, D. H. and Wright, J. H. (2005). An arbitrage-free three-factor term structure model and the recent behavior of long-term yields and distant-horizon forward rates. Finance and Economics Discussion Series 2005-33, Board of Governors of the Federal Reserve System (U.S.).

Kim, J. (2000). Constructing and estimating a realistic optimizing model of monetary policy. *Journal of Monetary Economics*, 45(2):329–359.

Kozicki, S. and Tinsley, P. A. (2001). Shifting endpoints in the term structure of interest rates. *Journal of Monetary Economics*, 47(3):613–652.

Krishnamurthy, A. and Vissing-Jorgensen, A. (2011). The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy. NBER Working Papers 17555, National Bureau of Economic Research.

Leeper, E. M. (1991). Equilibria under active and passive monetary and fiscal policies. *Journal of Monetary Economics*, 27(1):129–147.

Ljungqvist, L. and Sargent, T. (2004). *Recursive macroeconomic theory*. MIT Press.

Marzo, M., Söderström, U., and Zagaglia, P. (2008). The term structure of interest rates and the monetary transmission mechanism. Unpublished manuscript.

Marzo, M. and Zagaglia, P. (2011). Equilibrium selection in a cashless economy with transaction frictions in the bond market. MPRA Paper 31680, University Library of Munich, Germany.

Mehra, R. and Prescott, E. C. (1985). The equity premium: A puzzle. *Journal of Monetary Economics*, 15(2):145–161.

Piazzesi, M. and Schneider, M. (2006). Equilibrium yield curves. NBER Working Papers 12609, National Bureau of Economic Research.

Ravenna, F. and Seppälä, J. (2006). Monetary policy and the term structure of interest rates. Unpublished manuscript.

Rotemberg, J. J. (1982). Monopolistic price adjustment and aggregate output. *The Review of Economic Studies*, 49(4):517–531.

Rudebusch, G. D. (2010). Macro-finance models of interest rates and the economy. *The Manchester School*, 78:25–52.

Rudebusch, G. D., Sack, B. P., and Swanson, E. T. (2007). Macroeconomic implications of changes in the term premium. *Federal Reserve Bank of St. Louis Review*, 89:241–269.

Rudebusch, G. D. and Swanson, E. T. (2008). Examining the bond premium puzzle with a DSGE model. *Journal of Monetary Economics*, 55(Supplement 1):S111 – S126.

Rudebusch, G. D. and Swanson, E. T. (2009). The bond premium in a DSGE model with long-run real and nominal risks. Manuscript, Federal Reserve Bank of San Francisco.

Rudebusch, G. D. and Wu, T. (2007). Accounting for a shift in term structure behavior with no-arbitrage and macro-finance models. *Journal of Money, Credit and Banking*, 39(2-3):395–422.

Rudebusch, G. D. and Wu, T. (2008). A macro-finance model of the term structure, monetary policy and the economy. *Economic Journal*, 118(530):906–926.

Schmitt-Grohé, S. and Uribe, M. (2004). Optimal fiscal and monetary policy under imperfect competition. *Journal of Macroeconomics*, 26(2):183–209.

Smets, F. and Wouters, R. (2003). An estimated dynamic stochastic general equilibrium model of the Euro area. *Journal of the European Economic Association*, 1(5):1123–1175.

Smets, F. and Wouters, R. (2007). Shocks and frictions in us business cycles: A bayesian DSGE approach. *American Economic Review*, 97(3):586–606.

Taylor, J. B. (1993). Discretion versus policy rules in practice. *Carnegie-Rochester Conference Series on Public Policy*, 39:195–214.

Tobin, J. (1969). A general equilibrium approach to monetary theory. *Journal of Money, Credit and Banking*, 1(1):15–29.

Tobin, J. (1982). Money and finance in the macroeconomic process. *Journal of Money, Credit and Banking*, 14(2):171–204.

Uhlig, H. (2007). Explaining asset pricing with external habits and wage rigidities in a DSGE model. *American Economic Review*, 97(2):239–243.

van Binsbergen, J., Fernández-Villaverde, J., Koijen, R. S., and Rubio-Ramírez, J. F. (2010). The term structure of interest rates in a DSGE model with recursive preferences. Working Paper 15890, National Bureau of Economic Research.

Vayanos, D. and Vila, J.-L. (2009). A preferred-habitat model of the term structure of interest rates. Working Paper 15487, National Bureau of Economic Research.

Wright, J. (2011). Term premia and inflation uncertainty: Empirical evidence from an international panel dataset. *The American Economic Review*, 101(4):1514–1534.

Wu, T. (2006). Macro factors and the affine term structure of interest rates. *Journal of Money, Credit, and Banking*, 38(7):1847–1875.

Yang, J. (2008). Macroeconomic determinants of the term structure of corporate spreads. Working Paper 29, Bank of Canada.

Zagaglia, P. (2013). Forecasting long-term interest rates with a general-equilibrium model of the euro area: What role for liquidity services of bonds? *Asia-Pacific Financial Markets*, pages 1–48.

Tables

Table 1: Steady-state values of some variables

Notation	Description	SS values
Y	Output	1 (norm.)
C	Consumption-output ratio	0.57
T/Y	Taxes-output ratio	0.1972
$L/(1-L)$	Ratio of market to non-market activities	0.3
	Debt/GDP ratio	0.45
	Fraction of very short-term debt over total debt	0.233
	Fraction of short-term debt over total debt	0.142
	Fraction of medium-term debt over total debt	0.334
	Fraction of long-term debt over total debt	0.240
R	Gross money-market rate	1.01046
R_S	Gross short-term rate	1.00963
R_M	Gross medium-term rate	1.01070
R_L	Gross long-term rate	1.01428

Table 2: Benchmark calibration of the parameters

Notation	Description	Benchmark values
	Preferences and technology	
α	Share of capital in the production function	0.36
β	Intertemporal discount factor	0.9975
σ	Elasticity of intertemporal substitution	0.5
χ	Elasticity of money demand	7
ψ	Elasticity of labor supply	1
γ	Habit formation	0.7
θ	Elasticity of substitution between varieties of goods	6
ϕ_P	Price adjustment costs	100
ϕ_K	Capital adjustment costs	1143.9
	Fiscal and monetary policy	
ψ_0	Fiscal policy constant	0.1972
ψ_1	Fiscal policy response to b	0.3
ψ_2	Fiscal policy response to longer-term debt	0.3
α_π	Monetary policy response to inflation	1.5
α_Y	Monetary policy response to output	0
α_R	Monetary policy inertia	0.7
	Money-bonds transaction costs	
v_S	Short-term bonds	0.0030
v_M	Medium-term bonds	0.0040
v_L	Long-term bonds	0.0041
	OMOs parameters	
η_S	Short-term bonds	2.5
η_M	Medium-term bonds	2.5
η_L	Long-term bonds	7
	Autoregressive parameters	
ϕ_A	Technology shock	0.95
ϕ_G	Government spending shock	0.90
	Standard deviations	
σ_A	Technology shock	0.01
σ_G	Government spending shock	0.012
σ_R	Monetary policy shock	0.005

Table 3: U.S. term structure main statistics 1987:3-2011:3

	FFR	3-month	1-year	5-year	10-year	Spread
Standard deviation	2.522	2.288	2.390	2.051	1.788	1.382
Correlation with output gap	-	-	-	-	-	-0.656

Notes: Main moments of U.S. yields data: Federal funds rate (FFR), 3-month, 1-year, 5-year, and 10-year yields (constant-maturity interest rates, in percent per year). The spread is calculated as the difference between the 10-year yield and the FFR. Statistics computed using *Federal Reserve Economic Data.*

Table 4: Term structure moments in the benchmark calibration

	PR	ST	MT	LT	Spread	Term premium
Standard deviation	0.763	2.195	1.828	1.957	1.202	1.339
Corr. with output gap	-	-	-	-	-0.615	-0.326

Notes: Term structure moments of simulated data: Policy rate (PR), short-term rate (ST), medium-term rate (MT), long-term rate (LT). The spread is calculated as the difference between the long-term rate and the short-term rate. The term premium is calculated as explained in footnote 5.

Table 5: Term structure moments when varying money transaction costs

	PR	ST	MT	LT	Spread	Term premium
Benchmark values: $v_S = 0.0030$, $v_M = 0.0040$, $v_L = 0.0041$						
Standard deviation	0.763	2.195	1.828	1.957	1.202	1.339
Corr. with output gap	-	-	-	-	-0.615	-0.326
Increase of the costs: $v_S = 0.0060$, $v_M = 0.0080$, $v_L = 0.0081$						
Standard deviation	0.763	2.815	2.179	2.364	1.606	1.595
Corr. with output gap	-	-	-	-	-0.616	-0.306
Reduction in the costs: $v_S = 0.0015$, $v_M = 0.0020$, $v_L = 0.00205$						
Standard deviation	0.763	1.803	1.607	1.699	0.947	1.177
Corr. with output gap	-	-	-	-	-0.612	-0.343
No transaction costs: $v_S = v_M = v_L = 0$						
Standard deviation	0.763	1.340	1.346	1.391	0.647	0.987
Corr. with output gap	-	-	-	-	-0.602	-0.369

Notes: Term structure moments of simulated data when varying money transaction costs: Policy rate (PR), short-term rate (ST), medium-term rate (MT), long-term rate (LT). The spread is calculated as the difference between the long-term rate and the short-term rate. The term premium is calculated as explained in footnote 5.

Table 6: Term structure moments when varying the parameters of OMOs

	PR	ST	MT	LT	Spread	Term premium
Benchmark values: $\eta_S = 2.5$, $\eta_M = 2.5$, $\eta_L = 7$						
Standard deviation	0.763	2.195	1.828	1.957	1.202	1.339
Corr. with output gap	-	-	-	-	-0.615	-0.326
Higher skewness towards ST bonds: $\eta_S = 1.5$, $\eta_M = 9$, $\eta_L = 15$						
Standard deviation	0.763	2.317	1.782	1.933	1.178	1.286
Corr. with output gap	-	-	-	-	-0.613	-0.282
Higher skewness towards LT bonds: $\eta_S = 9$, $\eta_M = 4$, $\eta_L = 1.5$						
Standard deviation	0.763	2.071	1.799	2.148	1.399	1.547
Corr. with output gap	-	-	-	-	-0.623	-0.407

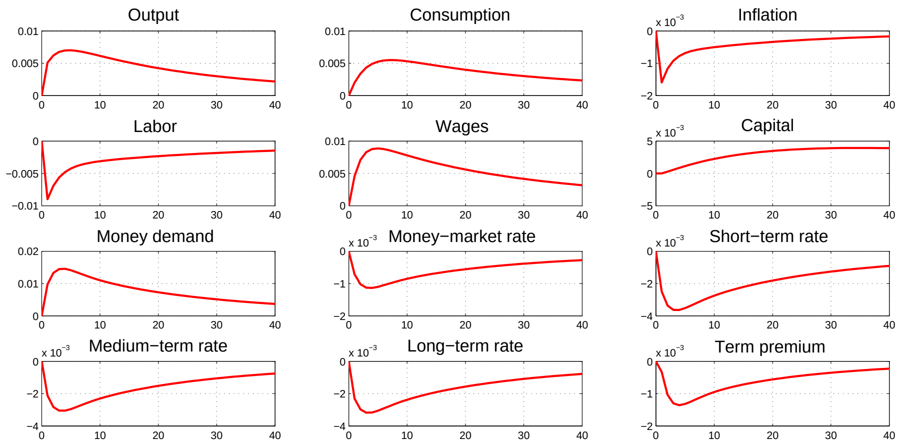
Notes: Term structure moments of simulated data when varying the parameters of open market operations: Policy rate (PR), short-term rate (ST), medium-term rate (MT), long-term rate (LT). The spread is calculated as the difference between the long-term rate and the short-term rate. The term premium is calculated as explained in footnote 5.

Table 7: Prior and posterior distribution (mean) of the parameters

Notation	Description	Prior distribution	Posterior distr.
	Preferences and technology		
σ	Elasticity of intertemporal substitution	Normal (1,0.5)	1.151
χ	Elasticity of money demand	Normal (7,3)	5.706
ψ	Elasticity of labor supply	Normal (1,0.5)	1.494
γ	Habit formation	Beta (0.7,0.3)	0.403
ϕ_P	Price adjustment costs	Normal (100,10)	102.767
	Monetary policy		
α_π	Monetary policy response to inflation	Normal (1.5,0.9)	2.197
α_Y	Monetary policy response to output	Normal (0.4,0.1)	0.461
α_R	Monetary policy inertia	Beta (0.5,0.2)	0.875
	Money-bonds transaction costs		
v_S	Short-term bonds	Normal (0.02,0.01)	0.0074
v_M	Medium-term bonds	Normal (0.02,0.01)	0.0166
v_L	Long-term bonds	Normal (0.05,0.01)	0.0100
	OMOs parameters		
η_S	Short-term bonds	Normal (2.5,2)	5.186
η_M	Medium-term bonds	Normal (2.5,2)	4.191
η_L	Long-term bonds	Normal (7,3)	8.737
	Autoregressive parameters		
ϕ_A	Technology	Beta (0.85,0.1)	0.750
ϕ_G	Government spending	Beta (0.85,0.1)	0.532
ϕ_M	Mark-up shock	Beta (0.85,0.1)	0.840
ϕ_π	Inflation targeting shock	Beta (0.85,0.1)	0.777
ϕ_{PR}	Preferences shock	Beta (0.85,0.1)	0.386
	Standard deviations		
σ_A	Technology shock	Inv. Gamma (0.4,2)	0.335
σ_G	Government spending shock	Inv. Gamma (0.5,2)	2.261
σ_R	Monetary policy shock	Inv. Gamma (0.4,2)	0.051
σ_M	Mark-up shock	Inv. Gamma (0.4,2)	0.271
σ_π	Inflation targeting shock	Inv. Gamma (0.1,2)	0.057
σ_{PR}	Preferences shock	Inv. Gamma (0.4,2)	0.399
σ_{BS}	ST bond supply shock	Inv. Gamma (0.4,2)	0.982
σ_{BM}	MT bond supply shock	Inv. Gamma (0.4,2)	1.034
σ_{BL}	LT bond supply shock	Inv. Gamma (0.4,2)	0.921

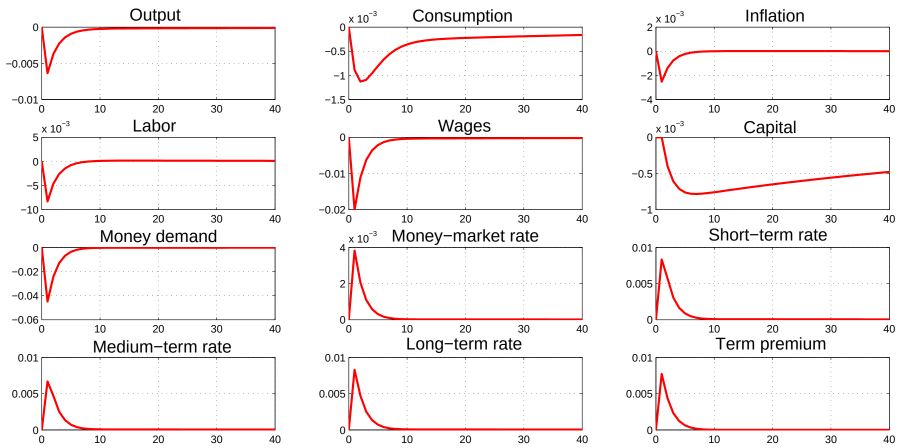
Figures

Figure 1: Impulse response functions to a positive technology shock



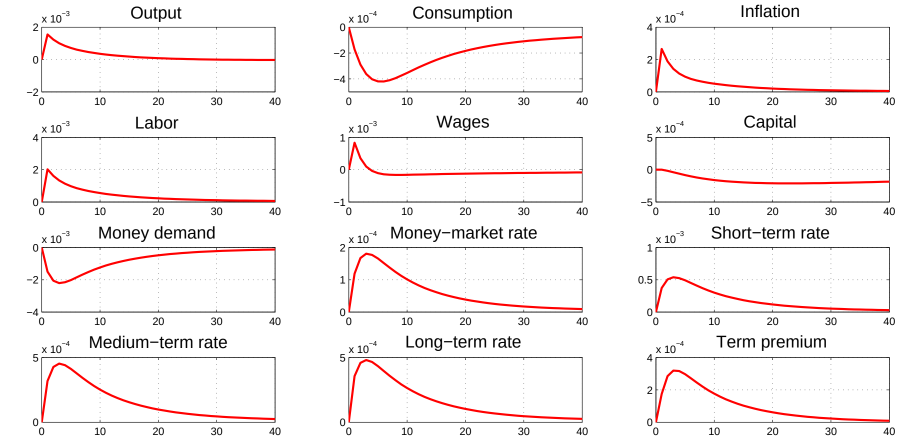
Notes: The impulse responses represent deviations from the steady-state level.

Figure 2: Impulse response functions to a contractionary monetary policy shock



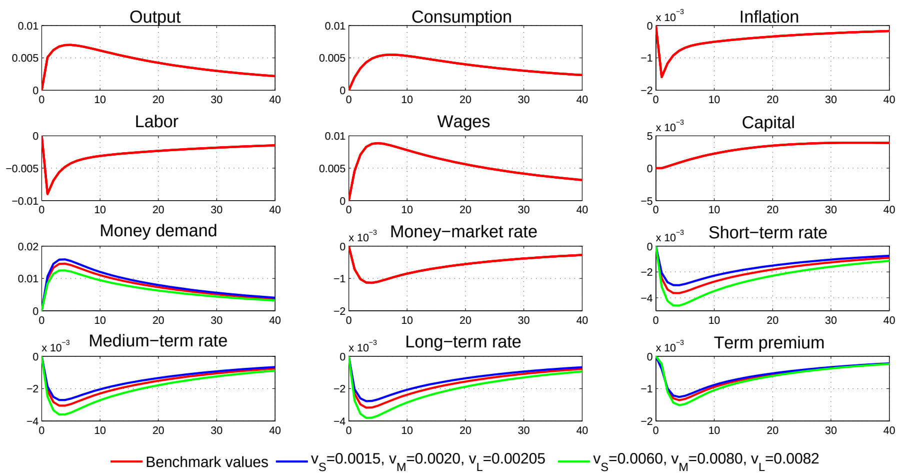
Notes: The impulse responses represent deviations from the steady-state level.

Figure 3: Impulse response functions to a government spending shock



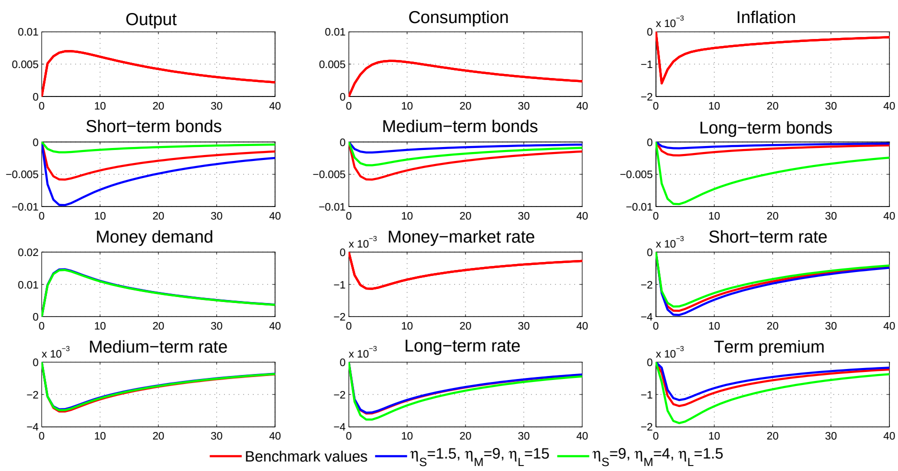
Notes: The impulse responses represent deviations from the steady-state level.

Figure 4: Impulse response functions to a positive technology shock when varying money transaction costs



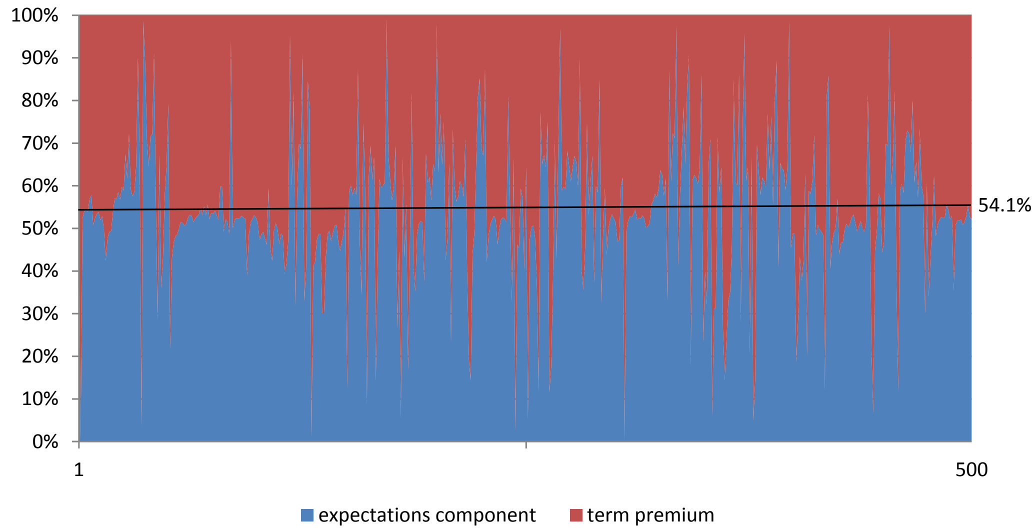
Notes: The impulse responses represent deviations from the steady-state level.

Figure 5: Impulse response functions to a positive technology shock when varying the parameters of OMOs



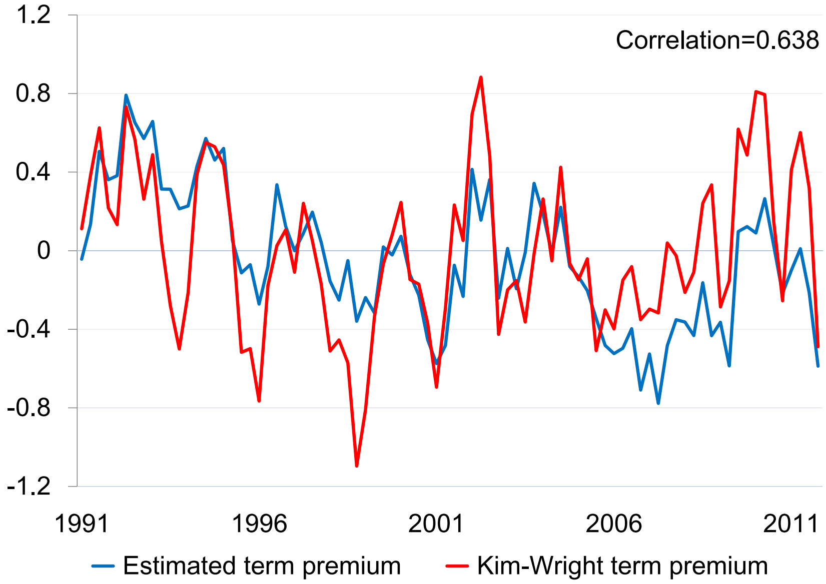
Notes: The impulse responses represent deviations from the steady-state level.

Figure 6: Decomposition of the yield spread - Benchmark model



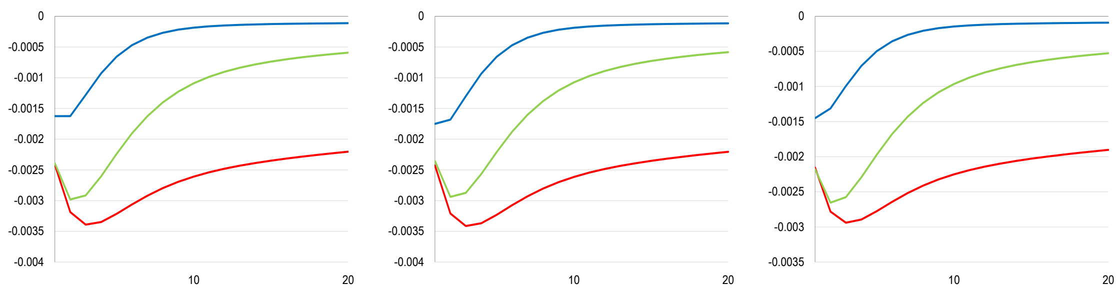
Notes: Yield spread decomposition into an expectation component and a term premium, as shown in equation (48).

Figure 7: The estimated term premium vs. Kim and Wright's (2005) term premium



Notes: Comparison between our estimated term premium and Kim and Wright (2005) term premium (1990:4-2011:3). The term premium by Kim and Wright (2005) has been detrended.

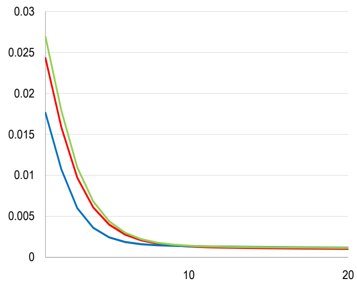
Figure 8: Posterior impulse responses (median) to a positive technology shock



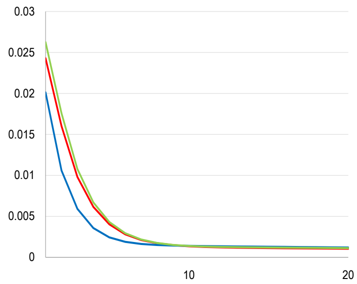
(a) Short-term rate (b) Medium-term rate (c) Long-term rate

Notes: The figure reports the median of the posterior impulse responses to a positive technology shock. The impulse responses represent deviations from the steady-state level. Red line: full sample period; Blue line: 1987:3-1998:1; Green line: 1998:2-2011:3.

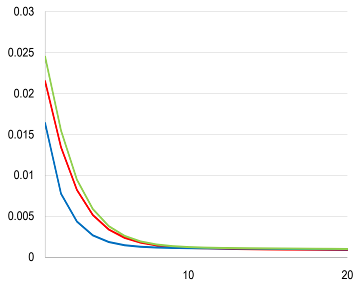
Figure 9: Posterior impulse responses (median) to a contractionary monetary policy shock



(a) Short-term rate



(b) Medium-term rate



(c) Long-term rate

Notes: The figure reports the median of the posterior impulse responses to a positive technology shock. The impulse responses represent deviations from the steady-state level. Red line: full sample period; Blue line: 1987:3-1998:1; Green line: 1998:2-2011:3.