Forecasting with a DSGE model of the term structure of interest rates: The role of the feedback

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Abstract

This paper studies the forecasting performance of the general equilibrium model of bond yields of Marzo, Söderström and Zagaglia (2008), where long-term interest rates are an integral part of the monetary transmission mechanism. The model is estimated with Bayesian methods on Euro area data. I investigate the out-of-sample predictive performance across different model specifications, including that of De Graeve, Emiris and Wouters (2009). The accuracy of point forecasts is evaluated through both univariate and multivariate accuracy measures. I show that taking into account the impact of the term structure of interest rates on the macroeconomy generates superior out-of-sample forecasts for both real variables, such as output, and inflation, and for bond yields.

KEYWORDS: Monetary policy, yield curve, general equilibrium, bayesian estimation.

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1 Introduction

Different frameworks have been proposed to study the relation between movements in the term structure of interest rates and business cycle fluctuations.[1] Most of the literature on 'macro-finance' uses reduced-form macroeconomic models that lack microfoundations (e.g., see Rudebusch and Wu, 2003 and Hördahl, Tristani, and Vestin, 2006). The obvious shortcoming of this approach is that the exogenous disturbances that drive the pricing of risk have typically no structural interpretation. Furthermore, bond yields at different maturities are priced in an *ad hoc* way because the 'pricing kernels' do not rest on well defined optimization problems of the consumer.

Various papers have tried to fill in this gap in the literature by modelling the macroeconomy through dynamic stochastic general equilibrium models (DSGE). In this way, bond yields can be priced by using kernels that are consistent with the utility function of a representative consumer. The modelling approaches of De Graeve, Emiris and Wouters (2009), Doh (2008) and Amisano and Tristani (2008) represent a few examples. De Graeve, Emiris and Wouters (2009) augment the loglinearized model of Smets and Wouters (2003) with model-consistent yields for longer maturities. In the Bayesian estimation, they introduce measurement errors in the yields to mimic term premia. Doh (2008) estimates the second-order Taylor approximation of a small-scale New Keynesian model with conditional heteroskedasticity of the structural shocks. Amisano and Tristani (2008) augment the second-order approximation of a small structural model with regime switching in the shocks.

The available contributions focus on generating a realistic variability in term premia that allows to match the observed changes in bond yields. However, they disregard the role that changes in the term structure of interest rates play for macroeconomic fluctuations. These models price the term structure by using the kernel for one period bonds. Since the kernel is extracted from the solution of the model economy, this pricing strategy ignores the issue of the 'feedback' from bond yields to the macroeconomy. While the these models imply effects of monetary policy and the macroeconomy on the term structure, they do not feature effects in the opposite direction, from the term structure (and term premia) to the macroeconomy and monetary policy.

The relevance of changes in asset prices for the monetary transmission mechanism is often stressed by prominent policymarkers. For instance, on April 28, 2009, during a keynote lecture at the International Center for Monetary and Banking Studies, Lorenzo Bini Smaghi, Member of the Executive Board of the European Central Bank, has reviewed the arguments for quantitative easing, suggesting that

> "*When long-term government bonds are purchased, the yields on privately issued securities are expected to decline in parallel with those on government bonds. (...) If long-term interest rates were to fall, this would stimulate longer-term investments and hence aggregate demand, thereby supporting price stability.*"

The role of the term structure for macroeconomic fluctuations was remarked also by Jean-Claude Trichet, president of the European Central Bank, during a Testimony before the Committee on Economic and Monetary Affairs of the European Parliament on September 14, 2005:

> "*(...) investment should benefit from the exceptionally low level of both nominal and real market interest rates prevailing across the entire maturity spectrum.*"

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[1] Extensive surveys are provided in Diebold, Piazzesi, and Rudebusch (2005) for the literature on affine term structure model, and in Rudebusch, Sack, and Swanson (2007) for bond pricing in macro models.

This is indicative of the conventional wisdom that, by affecting the term structure, a central bank can control part of the monetary transmission mechanism.

Despite the lack of feedback, the DSGE models of the term structure described earlier have been used for forecasting both government bond yields, and output and inflation. Failing to account for the feedback from bond yields can be a source of misspecification that affects the predictive ability of the model. In this paper, I investigate whether accounting for the role of the term structure in the monetary transmission mechanism delivers gains of predictive performance. I use Bayesian techniques to estimate the general equilibrium model of bond yields of Marzo, Söderström and Zagaglia (2008) on quarterly Euro area data for the period 1980:1 to 2007:2. Following Adolfson, Lindé and Villani (2007), I evaluate the out-of-sample rolling forecasts of the model using both univariate and multivariate accuracy criteria.

The framework of Marzo, Söderström and Zagaglia (2008) builds on the portfolio approach of Tobin (1969, 1982) to introduce segmentation in financial markets. Due to frictions that make changes in bond holdings costly to households, the model generates positive holdings of different types of bonds in equilibrium. In this paper, I use a version of the model with short, medium and long-term bonds. I assume that changing the ratios between the bond and money holdings generates a real cost for the household. The maturity profile of bonds is then determined by the propensity of households to reallocate resources between each bond and money. This mechanism creates a link between monetary aggregates and bond prices, and allows to study the role of money demand shocks when bond prices matter for the macroeconomy.

The model presents two channels of monetary transmission between the term structure and the real variables. Since long-term bonds are part of households' wealth, they determine the shadow value of the budget constraint and affect consumption choices. This is a standard wealth channel. When agents have a desire to hold a certain ratio between bonds of longer maturities and money, long-term rates generate changes in money demand. This is a money demand channel. By assuming that money provides liquidity services for the purchase of consumption goods, I strengthen the link between bond prices and consumption through money demand. Moreover, following Andrés, López-Salido and Vallés (2006), I introduce a money target target in the central bank's monetary policy rule. Since short-term interest rates respond to fluctuations of money demand around its long-run value, changes in long-term interest rates feed through to output via the pricing of short-term bonds.

In order to understand what feedback channels from the term structure are important for capturing the properties of the data, I compare the out-of-sample predictive performance of the benchmark DSGE model with those of alternative model versions.To get a flavor of how important the money demand channel is for the feedback, I estimate a model variant with strongly-separable utility between consumption and money, and without money target in the monetary policy rule. The question remains about how well the model of the term structure helps to understand changes in output and inflation. After removing the bond market frictions, I obtain a New Keynesian model with non-separability between consumption and money balances. The bond and money market frictions that generate endogenous long-term yields imply restrictions that are different from those of the expectations hypothesis of the term structure. Hence, an appropriate competing model for the term structure is that of De Graeve, Emiris and Wouters (2009).

The results suggest that removing the money demand channel for feedback worsens the predictive performance of the model both for the term structure yields and for money. The model with the endogenous term structure predicts output and inflation better than a model version without the term structure. This indicates that the modelling strategy for the term structure pursued in the benchmark DSGE conveys relevant information for the monetary transmission mechanism. Finally, the forecast comparison with the model of De Graeve, Emiris and Wouters (2009) accounting for the feedback through the financial market frictions presented here improves substantially the predictive performance for bond prices.

The paper is organized as follows. Section 2 outlines the model. The dataset is presented in Section 3. Section 4 discusses the calibrated parameters, the calculation of the deterministic steady state, and the prior assumptions. In Section 5 I comment on the parameter estimates. In Section 6 I describe the competing forecasting models. Section 7 outlines the forecast accuracy criteria. The results of the out-of-sample forecasting exercise are discussed in Section 8. Section 9 presents the concluding remarks.

2 The model

In this section, I develop a business cycle model with an endogenous term structure of interest rates, which is an integral part of the transmission of monetary policy. The starting point for our analysis is a New-Keynesian model with sticky prices, habits in consumption, and capital adjustment costs. To this model I add an endogenous term structure of interest rates by assuming that households allocate their assets among three different types of bonds, which I interpret as being of different maturity: short-term money market bonds, medium-term bonds, and long-term bonds. As households are assumed to face costs when adjusting their bond holdings, there is a non-zero demand for each type of bond, and the expectations hypothesis does not hold. Households also face transaction costs for money holdings, so the effect of term structure movements operate through households' money demand.

2.1 Households

There is a continuum of identical and infinitely-lived households indexed by $i \in [0, 1]$. (For convenience I omit the index i in what follows.) These households obtain utility from consumption of a bundle c_t of differentiated goods relative to an endogenous habit level, and disutility from labor ℓ_t according to the utility function

$$U\left(c_t, c_{t-1}, \ell_t\right) = E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{1}{1-1/\sigma}\left(c_t - \gamma c_{t-1}\right)^{1-1/\sigma} - \epsilon_t^{\ell} \frac{\Psi}{1+1/\psi} \ell_t^{1+1/\psi}\right], \tag{1}$$

where β is a discount factor, σ determines the elasticity of intertemporal substitution, γ determines the importance of habits, ψ is the elasticity of labor supply. The term c_t denotes a constant elasticity of substitution aggregator of differentiated goods

$$c_t = \left[\int_0^1 c_t(j)^{(\theta_{f,t}-1)/\theta_{f,t}} dj\right]^{\theta_{f,t}/(\theta_{f,t}-1)}, \tag{2}$$

with a time-varying elasticity $\theta_{f,t}$. The preference shock on labour supply ϵ_t^{ℓ} is

$$\ln(\epsilon_t^{\ell}) = \rho_\ell \ln(\epsilon_{t-1}^{\ell}) + \nu_t^{\ell}. \tag{3}$$

Households allocate their wealth among money holdings, accumulation of capital, which is rented to firms, and holdings of three types of nominal bonds. I interpret these different bonds as short-term money market bonds (denoted B_t), medium-term ($b_{M,t}$), and long-term bonds ($B_{L,t}$), which pay the returns $R_{M,t}$ and $R_{L,t}$, respectively.

I assume that money holdings do not provide direct utility to households. Rather, they generate transaction services for the purchase of consumption goods. This modelling strategy stresses the role of money as a medium of exchange and is adopted also in Sims (1994).[2]

In order to obtain a realistic internal propagation mechanism in the model, and to generate fluctuations of the rental rate of capital compatible with the empirical evidence, I introduce quadratic adjustment costs of investment along the lines of Abel and Blanchard (1983) and Kim (2000) with

$$AC_t^i = \frac{\phi_K}{2}\left(\frac{i_t}{i_{t-1}}\right)^2, \tag{4}$$

where k_t and i_t are, respectively, the levels of real capital and investment. The law of motion of the capital stock is given by

$$k_{t+1} = \epsilon_t^i \left(1 - AC_t^i\right) i_t + (1-\delta)k_t, \tag{5}$$

where δ is the depreciation rate of the capital stock, and ϵ_t^i is a shock to the relative price of investment goods

$$\ln(\epsilon_t^i) = \rho_i \ln(\epsilon_{t-1}^i) + \nu_t^i \tag{6}$$

with a white noise ν_t^i.

The representative household maximizes its life-time utility U_t subject to the budget constraint

$$\begin{aligned} &\frac{C_t}{P_t}(1+f(v_t)) + \frac{I_t}{P_t} + AC_t^W + \tau_t \\ &+ \frac{B_t}{P_t} + \frac{B_{M,t}}{P_t}\left(1+AC_t^M\right) + \frac{B_{L,t}}{P_t}\left(1+AC_t^L\right) + \frac{M_t}{P_t}\left(1+AC_t^m\right) \\ &\qquad = R_{t-1}\frac{B_{t-1}}{P_t} + R_{M,t-1}\frac{B_{M,t-1}}{P_t} + R_{L,t-1}\frac{B_{L,t-1}}{P_t} + \frac{M_{t-1}}{P_t} + \frac{W_t}{P_t}\ell_t + \frac{Q_t}{P_t}k_t + \Omega_t, \end{aligned} \tag{7}$$

where the AC_t^ι terms are different adjustment costs, to be specified below, P_t is the aggregate price level, and I_t is investment. The household obtains income from renting capital, k_t, to firms at the rental rate q_t, labour services, $w_t\ell_t$, where w_t is the real wage, and from its share in firms' real profits, Ω_t. Finally, households pay a real lump-sum tax τ_t.

The term $f(\cdot)$ indicates a transaction cost function expressed in terms of the consumption-money velocity $v_t := c_t/m_t$. Two types of transaction functions can be considered. A concave function allows the existence of a barter equilibrium with no money and a positive nominal rate of interest (see Sims, 1994). A convex function instead rules out the possibility of a barter equilibrium. In this paper, I use

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[2] Feenstra (1986) shows that including money through a transaction cost function is equivalent to modelling money directly in the utility function.

the quadratic function

$$f(v_t) = \epsilon_t^m \frac{(v_t)^2}{2}. \tag{8}$$

The money 'velocity' or money demand shock ϵ_t^ι follows an autoregressive process

$$\ln(\epsilon_t^m/\epsilon^m) = \rho_m \ln(\epsilon_{t-1}^m/\epsilon^m) + \nu_t^m. \tag{9}$$

with a positive deterministic steady state ϵ^m.

2.1.1 Household's bond portfolio

According to the traditional asset allocation theory, agents hold different types of assets in their portfolio depending on each asset's risk/return trade-off and expectations about the future path of this trade-off. For government bonds, the risk element is exclusively related to the uncertainty with respect to the future path of returns. The main difficulty when modelling assets with different rates of return in general equilibrium is due to the solution technique employed which, for computational reasons, typically involves Taylor approximations (up to first or second order) of the system of equations around the steady state. Of course, this procedure eliminates any role for higher-order terms, making it difficult to allow a full portfolio choice on the basis of the risk/return trade-off. I instead implement an alternative methodology that allows for the simultaneous presence of different rates of return on government bonds.

To ensure a non-zero demand for each bond, I follow Andrés, López-Salido and Nelson (2004) and generalize the Tobin (1969, 1982) model of portfolio allocation by inserting two types of portfolio adjustment frictions, which can be rationalized as transaction costs. In order to generate positive equilibrium holdings of different types of bonds, I assume that bond trading is costly to each agent. In particular, households face quadratic adjustment costs that are given by

$$AC_t^\iota = \frac{\phi_\iota}{2} \left(\frac{B_{\iota,t}/P_t}{B_{\iota,t-1}/P_{t-1}} \right)^2 y_t. \tag{10}$$

with $\iota = \{M, L\}$. The finance literature presents a large number of models that are based on transaction costs. The bond adjustment costs 10 formalize the idea that portfolio decisions are sluggish because agents have preferences over bond maturities. The 'theory of preferred habitat' of investors has recently been revived by Vayanos and Vila (2007) and Guibaud, Nosbusch and Vayanos (2008), who study the relation between risk premia and the maturity structure of government debt.

The adjustment cost is paid in terms of aggregate output y_t, an assumption that allows to better quantify the magnitude of these costs in terms of the budget for the representative household, and also implies that spreads between the different bonds returns vary over time. At the steady state, as long as $\phi_L \neq 0$ these adjustment costs are non-zero.

In order to capture the entire dimension of costs involved in any financial transaction, I also assume that there are transaction costs for money holdings. Since short-term bonds are money-market instruments, they are perfect substitute for money. This does not hold for the other types of bonds. The idea is to capture the risk propensity of households through the willingness to 'liquidate' a bond. Ideally, the larger the substitutability between long-term bonds and money, the more the households are willing to reallocate resources into money, and the larger the liquidity services that households can potentially use to smooth out consumption in each period.

The relationship of imperfect substitutability between money and money is formalized in the transaction cost function

$$AC_t^{\iota,m} = \frac{v_\iota}{2}\left(\frac{M_t/B_{\iota,t}}{M/B_\iota} - 1\right)^2 y_t. \tag{11}$$

The adjustment-cost function (11) implies that changes of bond holdings affect the money market as they generate movements in money demand. When there is an increase in the desired stock of a bond, households' demand for money increases in order to keep the money-bond ratio constant. This implies that the degree of imperfect substitutability between money and bonds affects the yields.[3]

The economic justification for the adjustment costs between bonds and money relies in the fact that one can think of the liquidity profile as a proxy for the behavior of agents towards risk (see Tobin, 1958). Since bonds are implicitly held until expiry in our model, the longer the maturity of a bond, the more limited its capability of providing opportunities for consumption smoothing until expiry, should negative shocks occur. This indicates that the household has a larger propensity to reallocate between bonds and money for bonds with longer maturities. In terms of priors on the parameters, the theory suggests $v_L < v_M$.

The adjustment costs are paid in terms of real output y_t, and they measure the amount of resources spent in order to shift the portfolio allocation between money and bonds at long maturities. Finally, the money/bond transaction costs are present only during the transition to the long-run equilibrium, and are zero at the steady state. Consequently, only the bond adjustment costs are present in steady state, and are therefore responsible for the different long-run rates of return.

2.1.2 Labour supply decision

Each household is a monopolistic supplier of an idiosyncratic labor service ℓ_{jt} indexed by j over a set m. Heterogenous labor inputs for the production of intermediate goods aggregate

$$\ell_t \leq \left[\int_{j\in m} \ell_{jt}^{\frac{1-\theta_{\ell,t}}{\theta_{\ell,t}}} dj\right]^{\frac{\theta_{\ell,t}}{1-\theta_{\ell,t}}}. \tag{12}$$

The elasticity of substitution across labor services $\theta_{\ell,t} > 1$ varies around a mean θ_ℓ

$$\theta_{\ell,t} := \theta_\ell + \epsilon_t^w \tag{13}$$

where ϵ_t^w is an autocorrelated shock to wage markups with variance σ_w.

Differentiation in the labor market is due to the decreasing marginal productivity of labor. Since

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[3] The money-bond transaction cost presented in this paper generates a sluggish reallocation of funds across bonds of different maturities. This is somewhat similar to the spirit of the mechanism discussed by Abel, Eberly and Panageas (2007). They propose a model of stock pricing where agents face a cost of moving funds between a consumption account, used to purchase goods, and an investment account, used to buy equity and bonds. However there are substantial differences in the economic motivation of the two approaches.

firms take the price of labor as given, the demand function for labor is

$$\ell_{jt} = \left[\frac{w_{jt}}{w_t}\right]^{-\theta_{\ell,t}} \ell_t \tag{14}$$

where w_{jt} is the real wage paid to household j. The wage index w_t prevailing in the economy takes the standard form:

$$w_t = \left[\int_{j\in m} w_{jt}^{1-\theta_{\ell,t}} dj\right]^{\frac{1}{1-\theta_{\ell,t}}} \tag{15}$$

Household j chooses the nominal wage rate for his idiosyncratic labor service. Since there is a large number of workers, each wage setter takes both w_t and ℓ_t as given. In order to mimic wage stickiness, I assume the presence of quadratic adjustment costs for nominal wages:

$$AC_t^W = \frac{\phi_w}{2}\left(\frac{W_{jt}}{W_{jt-1}} - \gamma_W \pi_t^* - (1-\gamma_W)\pi_{t-1}\right)^2 W_t \tag{16}$$

Equation 16 formalizes the idea that persistent deviations of the rate of change of nominal wages from an index of wage inflation are costly. I assume that the latter equals a weighted average of the central bank's inflation target π_t^*, and previous period's inflation. This formulation is also adopted in Ireland (2007), as well as in De Graeve, Emiris and Wouters (2009). The adjustment cost is expressed in units of nominal wages.

2.1.3 Optimality conditions

The optimal intra-temporal consumption choice implies the typical demand function

$$\frac{c_t(j)}{c_t} = \left[\frac{P_t(j)}{P_t}\right]^{-\theta_{f,t}}, \tag{17}$$

where P_t is the aggregate price index

$$P_t = \left[\int_0^1 (P_t(j))^{1-\theta_{f,t}} dj\right]^{1/(1-\theta_{f,t})}. \tag{18}$$

The elasticity of substitution of demand $\theta_{f,t}$ between intermediate goods is time-varying around a mean θ_f

$$\theta_{f,t} := \theta_f + \epsilon_t^P \tag{19}$$

where ϵ_t^P is an autocorrelated shock to price markups with variance σ_P.

Maximizing life-time utility in equation (1) subject to the budget constraint (7), and imposing symmetry of choices imply that the optimal inter-temporal consumption choice satisfies

$$(c_t - \gamma c_{t-1})^{-1/\sigma} - \beta\gamma \mathsf{E}_t (c_{t+1} - \gamma c_t)^{-1/\sigma} = \lambda_t \left[1 + \frac{3}{2}\epsilon_t^m \left(\frac{c_t}{m_t}\right)^2\right], \tag{20}$$

where λ_t is the marginal utility of consumption; the optimal wage choice follows from

$$\begin{aligned}\epsilon_t^{\ell}\Psi\frac{\theta_{\ell,t}}{w_t}\left(\ell_t\right)^{1+1/\psi} - \lambda_t\left[\phi_w\left(\frac{w_t}{w_{t-1}}\pi_t - \gamma_W\pi_t^* - (1-\gamma_W)\pi_{t-1}\right)\frac{w_t}{w_{t-1}}\pi_t - (1-\theta_{\ell,t})\ell_t\right]& \\ + \beta\mathsf{E}_t\lambda_{t+1}\phi_w\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - \gamma_W\pi_{t+1}^* - (1-\gamma_W)\pi_t\right)\left(\frac{w_{t+1}}{w_t}\right)^2\pi_{t+1} = 0,& \qquad (21)\end{aligned}$$

holdings of the money market bond follow

$$\beta\mathsf{E}_t\frac{R_t\lambda_{t+1}}{\pi_{t+1}} = \lambda_t; \qquad (22)$$

and holdings of the remaining two bonds satisfy

$$\begin{aligned}&\beta\mathsf{E}_t\frac{R_{\iota,t}\lambda_{t+1}}{\pi_{t+1}} + \beta\phi_\iota\mathsf{E}_t\left\{\lambda_{t+1}\left(\frac{b_{\iota,t+1}}{b_{\iota,t}}\right)^3 y_{t+1}\right\} \\ =\;& \lambda_t\left[1+\frac{3}{2}\phi_\iota\left(\frac{b_{\iota,t}}{b_{\iota,t-1}}\right)^2 y_t - \upsilon_\iota\kappa_\iota\left(\frac{m_t}{b_{\iota,t}}\right)^2\left(\frac{m_t}{b_{\iota,t}}\kappa_\iota - 1\right)\right], \qquad (23)\end{aligned}$$

for $\iota = M, L$, where $m_t = M_t/P_t$ are real money holdings, $b_{\iota,t} = B_{\iota,t}/P_t$ are real holdings of bond ι, and $\pi_t = P_t/P_{t-1}$ is the gross rate of inflation; Note that in the case without bond adjustment and transaction costs ($\phi_\iota = \upsilon_\iota = \kappa_\iota = 0$) the optimality conditions for the three bonds are identical, so all bonds give the same return. The different returns of the bonds thus arise from the presence of adjustment and transaction costs. Optimal money holdings evolve according to

$$\begin{aligned}\beta\mathsf{E}_t\frac{\lambda_{t+1}}{\pi_{t+1}} + \epsilon_t^m\left(\frac{c_t}{m_t}\right)^3 &= \lambda_t\left[1 + AC_t^{S,m} + AC_t^{L,m}\right] \\ &+ \lambda_t m_t\left[\upsilon_M\kappa_M\left(\frac{m_t}{b_{M,t}}\kappa_M - 1\right)\frac{y_t}{b_{M,t}} + \upsilon_L\kappa_L\left(\frac{m_t}{b_{L,t}}\kappa_L - 1\right)\frac{y_t}{b_{L,t}}\right]. \qquad (24)\end{aligned}$$

The first-order conditions for the capital stock and investment are

$$\beta\left(1-\delta\right)\mathsf{E}_t\mu_{t+1} = \mu_t - \lambda_t q_t, \qquad (25)$$

$$\lambda_t + \mu_t\epsilon_t^i\frac{3}{2}\phi_K\left(\frac{i_t}{i_{t-1}}\right)^2 = \mu_t\epsilon_t^i + \beta\mathsf{E}_t\mu_{t+1}\epsilon_{t+1}^i\phi_K\left(\frac{i_{t+1}}{i_t}\right)^3, \qquad (26)$$

where μ_t is the marginal value of capital.

2.2 Firms

Firms (indexed by $j \in [0,1]$) produce and sell differentiated final goods in a monopolistically competitive market. These goods are produced using capital and labor following the Cobb-Douglas production function

$$y_t(j) = \epsilon_t^a\left[k_t(j)\right]^\alpha\left[\ell_t(j)\right]^{1-\alpha} - \Phi, \qquad (27)$$

where a_t is a technology process given by

$$\ln\left(\epsilon_t^a/\epsilon^a\right) = \rho_a \ln\left(\epsilon_{t-1}^a/\epsilon^a\right) + \nu_t^a, \tag{28}$$

and ν_t^a is an i.i.d. shock with zero mean and constant variance σ_a^2. The term Φ denotes a fixed cost to ensure zero at the steady state

Firms set prices to maximize the expected future stream of profits subject to a quadratic price adjustment cost, following Rotemberg (1982). The price-adjustment cost function AC_t^P takes the form

$$AC_t^P = \frac{\phi_P}{2}\left(\frac{P_t}{P_{t-1}} - \gamma_P \pi_t^* - (1-\gamma_P)\pi_{t-1}\right)^2 y_t, \tag{29}$$

so price changes are costly as they deviate from a weighted average of steady state inflation and previous period's inflation.

The presence of price adjustment costs implies that the firm's price-setting problem is dynamic. The expected future profit stream is evaluated through a stochastic pricing kernel for contingent claims ρ_t, which plays the role of the firms' discount factor. However, assuming that each agent has access to a complete set of markets for contingent claims, the discount factors of firms and households are equal:

$$\mathsf{E}_t \frac{\rho_{t+1}}{\rho_t} = \beta \mathsf{E}_t \frac{\lambda_{t+1}}{\lambda_t}. \tag{30}$$

Each firm chooses its production inputs to maximize profits subject to the production function (27). The first-order conditions with respect to capital and labor are then given by

$$q_t = \alpha\left(1 - \frac{1}{e_t^y}\right)\left(\frac{y_t + \Phi}{k_t}\right), \tag{31}$$

$$w_t = (1-\alpha)\left(1 - \frac{1}{e_t^y}\right)\left(\frac{y_t + \Phi}{\ell_t}\right), \tag{32}$$

where I have omitted the index j and where e_t^y denotes the output demand elasticity, determined by

$$\begin{aligned}\frac{1}{e_t^y} = \frac{1}{\theta_{f,t}}\Bigg\{&1 - \phi_P\left(\pi_t - \gamma_P\pi_t^* - (1-\gamma_P)\pi_{t-1}\right)\pi_t \\ &+ \beta\phi_P \mathsf{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\left(\pi_{t+1} - \gamma_P\pi_{t+1}^* - (1-\gamma_P)\pi_t\right)\pi_{t+1}^2 \frac{y_{t+1}}{y_t}\right]\Bigg\}.\end{aligned} \tag{33}$$

Equation (33) measures the gross price markup over marginal cost. Without costs of price adjustment ($\phi_P = 0$), this markup is constant and equal to $\theta_f/(\theta_f - 1)$. With this formulation it is straightforward to see that all supply side shocks affect the magnitude and the cyclical properties of the markup.

2.3 The government sector

The government determines the level of taxes and bond supply, while the central bank determines the level of the money market interest rate.

The government budget constraint is given by

$$\frac{B_t}{P_t}+\frac{b_{M,t}}{P_t}+\frac{B_{L,t}}{P_t}+\frac{M_t}{P_t}+\tau_t = R_{t-1}\frac{B_{t-1}}{P_t}+R_{M,t-1}\frac{b_{M,t-1}}{P_t}+R_{L,t-1}\frac{B_{L,t-1}}{P_t}+\frac{M_{t-1}}{P_t}+g_t, \quad (34)$$

where g_t is government spending. For simplicity, define the government's total liabilities as

$$h_t := R_t\frac{B_t}{P_t}+R_{M,t}\frac{b_{M,t}}{P_t}+R_{L,t}\frac{B_{L,t}}{P_t}+\frac{M_t}{P_t}. \quad (35)$$

Then I can rewrite the government budget constraint as

$$h_t+\left(R_t-R_{M,t}\right)b_{M,t}+\left(R_t-R_{L,t}\right)b_{L,t}=\frac{R_t}{\pi_t}h_{t-1}+R_t\left(g_t-\tau_t\right)-(R_t-1)m_t \quad (36)$$

In order to close the model, I assume that the real supply of medium and long-term bonds follow the exogenous processes

$$\ln\left(b_{\iota,t}/b_\iota\right) = \rho_\iota \ln\left(b_{\iota,t-1}/b_{\iota)}\right)+\nu_t^\iota, \quad (37)$$

for $\iota = M, L$, where ν_t^ι are i.i.d. shocks with zero mean and constant σ_ι^2. An exogenous supply for bonds in an asset pricing model has also been introduced recently in Piazzesi and Schneider (2007), who study the impact of asset quantities on portfolio allocation in a partial equilibrium model.[4]

To avoid the emergence of inflation as a fiscal phenomenon, as in Leeper (1991), I assume a feedback rule for fiscal policy such that the total amount of tax collection is a function of the total government's liabilities outstanding in the economy:

$$T_t=\psi_0+\psi_1\left(h_{t-1}-h\right), \quad (38)$$

where T_t is nominal lump-sum taxes. I assume that government expenditure follows the exogenous AR(1) process

$$\ln\left(g_t/g\right)=\rho_g\ln\left(g_{t-1}/g\right)+\nu_t^g, \quad (39)$$

where ν_t^g is a disturbance term with zero mean and variance σ_g^2.

2.4 Monetary policy

The central bank is assumed to set the money market interest rate R_t according to the Taylor (1993) rule

$$\ln\left(\frac{R_t}{R}\right)=\alpha_R\ln\left(\frac{R_{t-1}}{R}\right)+(1-\alpha_R)\left\{\ln\left(\frac{\pi_t^*}{\pi}\right)+\alpha_\pi\left[\ln\left(\frac{\pi_t}{\pi}\right)-\ln\left(\frac{\pi_t^*}{\pi}\right)\right] +\alpha_y\ln\left(\frac{y_t}{y}\right)+\alpha_m\ln\left(\frac{m_t}{m_{t-1}}\pi_t\right)\right\}+\epsilon_t^R, \quad (40)$$

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[4] There is a large literature on the relation between the supply of bonds and the yields (e.g. see Greenwood and Vayanos, 2008, and Krishnamurthy and Vissing-Jorgensen, 2008.

where hats denote log deviations from the deterministic steady state. The autoregressive shock ϵ_t^R captures non-systematic monetary policy. The policy rate is determined as a function of the deviations of inflation, output and nominal money from the respective targets with a gradual adjustment. The central bank targets the level of output y at the steady state. The policy rule features a time-varying inflation target π_t^* along the lines of Smets and Wouters (2003)

$$\ln\left(\frac{\pi_t^*}{\pi}\right) = \rho_\pi \ln\left(\frac{\pi_{t-1}^*}{\pi}\right) + \nu_t^\pi \tag{41}$$

around the long-run value of inflation π, with an autoregressive shock ϵ_t^π.

Following Andrés, López-Salido and Nelson (2004) and Andrés, López-Salido and Vallés (2006), I allow for an additional channel of propagation of money demand shocks through the central bank's reaction function. This can be thought of as mimicking the scope for the 'monetary pillar' of the ECB.

2.5 Resource constraints

The model is completed by the aggregate resource constraint

$$\begin{aligned} y_t = c_t &\left(1 + \frac{\epsilon_t^m}{2}\left(\frac{c_t}{m_t}\right)^2\right) + i_t + g_t + \frac{\phi_P}{2}\left(\pi_t - \gamma_P \pi_t^* - (1-\gamma_P)\pi_{t-1}\right)^2 y_t \\ &+ \frac{\phi_w}{2}\left(\frac{w_t}{w_{t-1}}\pi_t - \gamma_W \pi_t^* - (1-\gamma_W)\pi_{t-1}\right)^2 w_t \\ &+ \left[b_{M,t}\frac{\phi_S}{2}\left(\frac{b_{M,t}}{b_{M,t-1}}\right)^2 + b_{L,t}\frac{\phi_L}{2}\left(\frac{b_{L,t}}{b_{L,t-1}}\right)^2\right] y_t \\ &+ m_t\left[\frac{v_M}{2}\left(\frac{m_t}{b_{M,t}}\kappa_M - 1\right)^2 + \frac{v_L}{2}\left(\frac{m_t}{b_{L,t}}\kappa_L - 1\right)^2\right] y_t. \end{aligned} \tag{42}$$

Thus, total output is allocated to consumption, investment, government spending, the price and wage adjustment costs, and the sum of adjustment costs for bond and money holdings.

2.6 An overview of the feedback from the term structure

The model features imperfect substitution between assets through costs of changing the ratio between medium and long-term bonds and money holdings. Also, the indivisibility between consumption and money establishes a direct link between money holdings and consumption decisions. These two characteristics together imply that the log-linearized demand for money depends on the money market rate, the quantities of bonds with medium and long maturities, and consumption

$$\begin{aligned} \frac{\beta}{\pi}\lambda E_t\hat{\lambda}_{t+1} - \frac{\beta}{\pi}\lambda E_t\hat{\pi}_{t+1} = &\left[3\epsilon^m\left(\frac{c}{m}\right)^3 + (v_M + v_L)\lambda y\right]\hat{m}_t \\ &+ \lambda\hat{\lambda}_t - 3\epsilon^m\left(\frac{c}{m}\right)^3\hat{c}_t - v_M\lambda\frac{y}{m}\hat{b}_{M,t} - v_L\lambda\frac{y}{m}\hat{b}_{L,t} - \epsilon^m\left(\frac{c}{m}\right)^3\hat{\epsilon}_t^m. \end{aligned} \tag{43}$$

Holdings of short-term bonds adjust in a frictionless way, and are priced from expected changes in the marginal utility consumption

$$\hat{R}_t + E_t\hat{\lambda}_{t+1} - E_t\hat{\pi}_{t+1} = \hat{\lambda}_t. \tag{44}$$

The expectations hypothesis of the term structure does not hold in the model because of the presence of frictions in the bond market. The prices of medium and long-term bonds respond to variations in bond quantities and money

$$\begin{aligned} &\beta\frac{R_\iota}{\pi}\lambda\hat{R}_{L,t} + \beta\lambda\left(\frac{R_\iota}{\pi} + \phi_\iota y\right)E_t\hat{\lambda}_{t+1} \\ &\qquad - \beta\frac{R_\iota}{\pi}\lambda E_t\hat{\pi}_{t+1} + \beta\phi_\iota\lambda y E_t\hat{y}_{t+1} + 3\beta\phi_\iota\lambda y E_t\hat{b}_{L,t+1} = \\ &\qquad\qquad \lambda\left(1 + \frac{3}{2}\phi_\iota y\right)\hat{\lambda}_t + \frac{3}{2}\lambda\phi_\iota y\hat{y}_t - 3\phi_\iota\lambda y\hat{b}_{L,t-1} \\ &\qquad\qquad\qquad + \left[3\phi_\iota\lambda y(1+\beta) - \lambda v_\iota y\frac{m}{b_\iota}\right]\hat{b}_{L,t} + \lambda v_\iota\frac{m}{b_\iota}y\hat{m}_t \end{aligned} \tag{45}$$

for $\iota \in \{M, L\}$. Since the bond adjustment costs penalize changes in bond holdings across periods, both lagged and expected quantity variations affect the pricing.

The financial market frictions outlined in this paper generate a feedback from the term structure to the macroeconomy through three channels. The first one follows from the presence of bond adjustment costs that are positive at the steady state. These costs generate a depletion of aggregate resources that is reflected directly in the log-linearized resource constraint

$$\begin{aligned} &\left(1 - b_M\frac{\phi_S}{2} - b_L\frac{\phi_L}{2}\right)y\hat{y}_t = \left[1 + \frac{3}{2}\epsilon^m\left(\frac{c}{m}\right)^2\right]c\hat{c}_t + i\hat{i}_t + g\hat{g}_t \\ &\qquad + (\phi_S y)b_M\hat{b}_{M,t-1} + (\phi_L y)b_L\hat{b}_{L,t-1} + \frac{3}{2}(\phi_S y)b_M\hat{b}_{M,t} + \frac{3}{2}(\phi_L y)b_L\hat{b}_{L,t} \\ &\qquad\qquad - \epsilon^m\left(\frac{c}{m}\right)^3 m\hat{m}_t + \epsilon^m\frac{c}{2}\left(\frac{c}{m}\right)^2\hat{\epsilon}^m_t. \end{aligned} \tag{46}$$

The other two feedback channels arise from the interplay between the imperfect substitutability of assets on one hand, and the consumption-money friction on the other.

The pricing equation 44 for the money market instrument can be used to rewrite the Euler equation 45 for medium and long-term bonds in terms of spreads from the short-term interest rate. The resulting expression provides a law of motion for the evolution of the money-bond ratios at medium and long-term, and can then be substituted into the equilibrium demand for money 43. The reduced-form demand for money is a function of all the yields from the structure.[5] At the same time, the presence of a transaction friction between consumption and money in the long run implies that changes in money demand affect the dynamics of output directly through the resource constraint 46. Money demand

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[5] The expression is not reported for it is algebraically cumbersome.

also determines the household's consumption plan,

$$\begin{aligned}&\frac{\gamma}{\sigma}(1-\gamma)^{-1/\sigma-1} c\hat{c}_{t-1} - \left[\frac{1}{\sigma}\left(1+\beta\gamma^2\right)(1-\gamma)^{-1/\sigma-1} + 3\lambda\epsilon^m\left(\frac{c}{m}\right)^2\right]\hat{c}_t \\ &\quad + \frac{\gamma}{\sigma}\beta(1-\gamma)^{-1/\sigma-1} E_t\hat{c}_{t+1} = \left(1+\epsilon^m\frac{c}{m^2}\right)\lambda\hat{\lambda}_t - 3\lambda\epsilon^m\left(\frac{c}{m}\right)^2\hat{m}_t + \frac{3}{2}\lambda\epsilon^m\left(\frac{c}{m}\right)^2\hat{\epsilon}^m_t, \quad (47)\end{aligned}$$

which feeds through to aggregate output. Finally, the short-term rate responds directly to changes in money demand (see eq. 40).

3 Data

The model is estimated on aggregate Euro-area data at a quarterly frequency for a period spanning from 1980:1 to 2007:2. I use twelve observable variables consisting of output, consumption, investment, wages, employment heads, inflation, a monetary aggregate, a money market rate, a medium and a long-term interest rate.[6]

A proper series for hours worked is not available. Like Smets and Wouters (2003), I estimate the model using a measure of employment heads. I link the observable to hours by assuming that only a fraction ξ_e of firms can adjust the stock of employees $\hat{e}_t$ as a function of the desired labour input

$$\hat{e}_t = \beta\hat{e}_{t+1} + \frac{(1-\beta\xi_e)(1-\xi_e)}{\xi_e}\left(\hat{\ell}_t - \hat{e}_t\right), \quad (48)$$

where all the variables are expressed as log-deviations from the steady state.

Yield curve data include average interest rates on bonds of maturities at 3 month, 2 and 10 years. The series for money demand consists of an indicator for M3. Finally, the inflation rate is obtained from the first difference of the harmonized index of consumer prices (HICP) at a quarterly frequency.

The original data series for the yields and M3 are available at a monthly frequency. They are aggregated as quarterly averages. Prior to estimation, all the series are deflated by the level of the HICP. The dataset is then detrended using a linear trend. For the interest rates, I use the trend of the inflation rate. The data series are plotted in Figure 1.

4 Estimation methodology

The optimality conditions of the model are loglinearized to obtain a system of linear rational expectations equations.[7] The system is solved through standard methods,[8] and the solution is cast in state-space form

$$\begin{aligned} Y_t &= A(\Theta) + B(\Theta)s_t + u_t && (49)\\ s_t &= \Phi_1(\Theta)s_{t-1} + \Phi_\epsilon(\Theta)\epsilon_t, && (50)\end{aligned}$$

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[6] The data have been downloaded from the Statistical Data Warehouse of the ECB.

[7] Appendix A presents the loglinearized system.

[8] In particular, I use the gensys algorithm of Chris A. Sims.

where Θ denotes the parameter vector, equation 49 is a measurement equation, and equation 50 is a state-transition equation. Given a data sample $Y^T := \{y_1, \dots y_T\}$, the likelihood function

$$\mathcal{L}\left(\Theta|Y^T\right) = \prod_{t=1}^{T} p(y_t|Y^{T-1}, \Theta) \tag{51}$$

is then evaluated using a Kalman filter. Given a set of priors $p(\Theta)$, the posterior distribution

$$p(\Theta|Y^T) \propto \mathcal{L}\left(\Theta|Y^T\right) p(\Theta) \tag{52}$$

is maximized with respect to Θ through a Random Walk Metropolis Hastings Algorithm. The parameter space consists of 36 parameters, out of which 14 determine the non-stochastic part of the model

$$\Theta_1 := [\ \sigma,\ \gamma,\ \psi,\ \phi_K,\ \phi_P,\ \gamma_P,\ \phi_W,\ \gamma_W,\ \xi_e,\ v_M,\ v_L,\ \alpha_R,\ \alpha_\pi,\ \alpha_y\ ]\,, \tag{53}$$

and 22 are related to the exogenous shocks

$$\begin{aligned} \Theta_2 &:= [\ \rho_m,\ \rho_\ell,\ \rho_i,\ \rho_a,\ \rho_P,\ \rho_w,\ \rho_g,\ \rho_M,\ \rho_L,\ \rho_R,\ \rho_\pi\ ]\,, && (54)\\ \Theta_3 &:= [\ \sigma_m,\ \sigma_\ell,\ \sigma_i,\ \sigma_a,\ \sigma_P,\ \sigma_w,\ \sigma_g,\ \sigma_M,\ \sigma_L,\ \sigma_R,\ \sigma_\pi\ ]\,. && (55)\end{aligned}$$

Since there are more shocks than observable variables, I do not introduce measurement errors.[9]

4.1 Calibrated parameters

A number of parameters are calibrated to match the long-run values of the observables, consistently with the steady state relations of the model discussed in Appendix B.. I also fix some parameters because the dataset is uninformative for their estimation. Their values are reported in Table 1.

The discount factor β is calibrated from the long-run relation between inflation and the short-term rate. The depreciation rate δ is 2.5% per quarter. Given a labor-income share in total output of 70%, I set α to 0.3. From an investment-output ratio equal to 0.2, I calibrate the fixed cost of production. The steady-state markups for prices and wages are calibration to 1.2 and 1.05, respectively, following Christiano, Motto and Rostagno (2007).

The bond-adjustment costs are not estimated because they are pinned down from the steady-state spreads between the yields. These parameters measure the share of income that households forego against a portfolio of assets. As argued in section 2.1.1, this generates positive holdings of different bonds in the long run. The economic intuition is that holding bonds of different maturities generates different opportunity costs in terms of output foregone. However, these bond holdings generate an array of yields. In the long run, the yields are tied to the opportunity costs of holding securities. Hence, for medium and long-term bonds, the adjustment costs are chosen to match average yields reported in Table 1. This gives $\phi_M = 0.0006$ and $\phi_L = 0.007$.

The debt to GDP ratio in steady state is set to 45 percent. Data on the maturity structure of public debt are only at an annual frequency from Missale (1999) and from the OECD Dataset. In this paper, I use the OECD series available for the period 1995-2005. Since the statistics are reported on

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[9] A number of estimation trials show that removing estimation errors improves the likelihood.

a country basis, I take simple averages of maturity shares for the available EMU countries, namely Belgium, Germany, Italy, the Netherlands, Portugal and Spain. The ratio of public spending to GDP in steady state is 19.86 percent, while the tax to GDP ratio is 19.72 percent.

The feedback parameter ψ_1 on the fiscal policy rule is of special interest because it largely affects the determinacy properties of the model. I fix it to 0.92 which, within the range of reasonable values, should yield fiscal policy as 'passive' in the sense of Leeper (1991). In this sense, lump-sum taxes are not allowed to act independently from the outstanding stock of government's liabilities, and are set to avoid an explosive path for public debt.

4.2 Prior distributions

The priors are reported in the second column of Table 2. The assumptions on the prior distributions are largely similar to those of Smets and Wouters (2003). All the variances of the shocks follow an inverted Gamma distribution with two degrees of freedom, so that the estimates fall in the region of positive values. The autoregressive parameters of the shocks have a Beta prior distribution with a small standard error. Most of the preference and technology parameters follow either a Normal or a Beta distribution with means consistent with previous studies. The intertemporal elasticity of substitution has a prior mean equal to one, consistently with the log utility in consumption that is typically used in estimated models (e.g. see Christiano, Motto and Rostagno, 2007). For the parameters on the adjustment cost functions for investment, prices and wages, I assumed a diffuse prior with starting values. These prior means are broadly in line with the available estimated models the U.S. economy (see Laforte, 2003 and Kim 2000), but lower than the values used in calibrated models of the Euro area (e.g. see Bayoumi, Laxton and Pesenti, 2004). After some preliminary estimation trials, I choose rather diffuse priors on the adjustment cost parameters between bonds and money. The model theory of imperfect substitutability between money and bonds suggests that the longer the maturity of a bond, the more households should be willing to 'liquidate' the bond. Hence the prior means should be such that $v_M > v_L$.[10] Finally, there are rather standard priors on the parameters of the Taylor rule. However, since the shape of the parameter regions that generate unique equilibria are unknown due to the new features of the model, the prior mean on the inflation coefficient is larger than usual, and the prior distribution has a higher standard deviation.

5 Alternative forecasting models

5.1 Competing DSGE models

I consider a number of variants of the 'benchmark' DSGE that allow to understand the contribution of model features to the predictive power. In the first set of competing models I remove various frictions from the benchmark specification and I re-estimate the resulting model. In particular, I estimation a version with flexible prices by fixing $\phi_P = 0.001$, without adjustment costs between bonds and money ($v_M = v_L = 0$), without consumption habits ($h = 0$), and without money target in the Taylor rule ($\alpha_m = 0$). I also study the forecast performance of models with fewer exogenous shocks than for the

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[10] It should be stressed that this restriction is not imposed in the estimation. Rather its plausibility will be confirmed by the results.

benchmark. I estimate model versions without shock to the inflation target ($\sigma_\pi = 0.0001$), without money velocity shock ($\sigma_M = 0.0001$), and without price markup shock ($\sigma_P = 0$).

To assess the importance of the key features of the benchmark DSGE model, I compare its out-of-sample forecasting performance with that of alternative models. In particular, I investigate how important the role of the feedback of the term structure to output is by considering a version of the model with strong separability in money and consumption, and without money growth in the Taylor rule. This amounts to estimating a model with the utility function

$$U\left(c_t, c_{t-1}, m_t, \ell_t\right) = E_0 \sum_{t=0}^{\infty} \beta^t \left[\epsilon_t^p \frac{1}{1-1/\sigma} \left(c_t - \gamma c_{t-1}\right)^{1-1/\sigma} \right. \\ \left. + \epsilon_t^m \frac{\Lambda}{1-\chi} \left(m_t\right)^{1-\chi} - \epsilon_t^\ell \frac{\Psi}{1+1/\psi} \ell_t^{1+1/\psi} \right]. \quad (56)$$

where γ is the elasticity of money demand, Λ is a parameter that helps matching the long-run money-output ratio, and ϵ_t^m is an autoregressive money demand shock. I also include a consumption preference shock with the standard autoregressive form. This shock is a source of exogenous variability for the stochastic discount factor, and helps matching the volatility of the rates without creating additional identification problems during the estimation. Optimal consumption plans are set according to

$$\left[(1-\gamma)c\right]^{1/\sigma} \lambda \hat{\lambda}_t = \frac{\beta}{\sigma} \frac{\gamma}{1-\gamma} E_t \hat{c}_{t+1} + \frac{1}{\sigma} \frac{\gamma}{1-\gamma} \hat{c}_{t-1} - \frac{1}{\sigma} \frac{1+\beta\gamma^2}{1-\gamma} \hat{c}_t, \quad (57)$$

and the money demand equation becomes

$$\Lambda m^{-\chi} \hat{\epsilon}_t^m - \left[\Lambda \chi m^{-\chi} + (\upsilon_M + \upsilon_L)\lambda y\right] \hat{m}_t + \frac{\beta}{\pi} \lambda E_t \hat{\lambda}_{t+1} - \frac{\beta}{\pi} \lambda E_t \hat{\pi}_{t+1} = \\ \lambda \hat{\lambda}_t - \upsilon_M \lambda \frac{y}{m} \hat{b}_{M,t} - \upsilon_L \lambda \frac{y}{m} \hat{b}_{L,t}. \quad (58)$$

The central bank sets the policy rate according to the standard Taylor rule

$$\hat{R}_t = \alpha_R \hat{R}_{t-1} + (1-\alpha_R)\left[\hat{\pi}_t^* + \alpha_\pi \left(\hat{\pi}_t - \hat{\pi}_t^*\right) + \alpha_y \hat{y}_t\right] + \nu_t^R. \quad (59)$$

When estimating this model version with Bayesian methods, all the prior assumptions are the same as those of the benchmark model. Measurement errors are not used because they cause a drop in the value of the likelihood.

The following question of interest is whether the relation between the term structure and money demand conveys information relevant for understanding changes in output and inflation. Hence I estimate a version of the DSGE without medium and long-term rates. In other words, I remove the bond adjustment costs and the adjustment costs between bonds and money. The resulting DSGE is a prototype New Keynesian model with transaction costs between consumption and money, price and wage rigidity arising from quadratic adjustment costs. Bond supply shocks drop out of the model. The priors are the same as for the benchmark model.

De Graeve, Emiris and Wouters (2009) price the term structure by computing yields $\hat{R}_t^n$ of n-period bonds that are consistent with the expectations hypothesis

$$\hat{R}_t^n = \frac{1}{n} E_t \sum_{j=1}^{1} \hat{R}_{t+j-1}. \tag{60}$$

These term-structure yields are a function of the solution of the loglinearized model. The equations for the expectations-consistent yields can be appended to the DSGE model. The augmented DSGE is then estimated as a system using standard Bayesian methods. In order to match the volatility of the observed yields, and to capture time variation in term premia, measurement errors are included to the state-space form. In particular, the measurement equation now reads

$$\begin{bmatrix} Y_t \\ R_t^n \end{bmatrix} = \begin{bmatrix} s \\ R^n \end{bmatrix} + \begin{bmatrix} \hat{s}_t \\ \hat{R}_t^n \end{bmatrix} + \begin{bmatrix} 0 \\ \eta_t^n \end{bmatrix} \tag{61}$$

Summing up, I augment the standard version of the New Keynesian model (without endogenous term structure) with two equations for the expectation-consistent pricing of bonds with maturity of 3 and 10 years. The model includes also measurement errors on medium and long-term yields.

For the estimation of all the models described in this section, I use the same prior assumptions of the benchmark. The priors for the measurement errors of the model of De Graeve, Emiris and Wouters (2009) are as follows. The standard deviations of both shocks have a uniform prior with mean 1.5 and standard deviation 1.5. The correlation of the measurement errors has a uniform prior with mean 0 and standard deviation 0.8.

5.2 Competing unrestricted models

I compare the out-of-sample performance of the benchmark DSGE model with that of a VAR system

$$\Phi(L)Y_t = \Phi + v_t \tag{62}$$

where $\Phi(L) = I_p - \Pi_1 L \ldots - \Pi_k L^k$, with the back-shift operator $LY_t = Y_{t-1}$. The disturbances $v_{tp}(0, \Sigma_v)$ are independent across time. The VAR is estimated on the twelve series that are used to estimate the DSGE.

The prior proposed by Litterman (1986) will be used on the dynamic coefficients in Π, with the following default values on the hyperparameters: overall tightness is equal to 0:3, and cross-equation tightness is set to 0.2 and a harmonic lag decay with a hyperparameter equal to one. I use the non-informative prior $|\Sigma_b|^{-(p+1)/2}$ for Σ_v. The posterior distribution of the model parameters and the forecast distribution of the endogenous variables were computed numerically using the Gibbs sampling algorithm in Kadiyala and Karlsson (1997). I report only the results from the VAR and BVAR with three lags. The forecasting results are similar across lag-lengths, with slight improvements delivered by the models with three lags.

6 Forecast accuracy criteria

The predictive performance of the model is evaluated on rolling forecasts from the DSGE model against a variety of competing models. In practice, each model is estimated until 2002:4. The forecast evaluation starts in 2003:1. The models are re-estimated each quarter by updating the information set with one data point. The dynamic forecast distribution is then computed. The procedure continues until no data are available to evaluate the one period ahead forecast.

In this paper, I consider evaluation criteria for both point and density forecasts. Denote by $e_t(h) = Y_{t+h} - \hat{Y}_{t+h|t}$ the h-step ahead error of the posterior mode forecast $\hat{Y}_{t+h|t}$ at time t. The standard measure of forecast accuracy is the usual root mean squared error (RMSE)

$$RMSE_i(h) = \sqrt{N_h^{-1} \sum_{t=T}^{T+N_h-1} e_{i,t}^2(h)} \tag{63}$$

where $e_{i,t}$ is the i-th element of $e_t(h)$, and N_h denotes the number of h step ahead forecasts.

I also consider a multivariate measure of forecast accuracy based on the h-step ahead Mean Squared Error matrix

$$\Omega_M(h) = N_h^{-1} \sum_{t=T}^{T+N_h-1} \tilde{e}_t(h)\tilde{e}_t(h)' \tag{64}$$

with $\tilde{e}_t(h) := M^{-1/2}e_t(h)$. The term M indicates a scaling matrix acts as a scaling matrix that accounts for the differing scales of the forecasted variables. A number of scalar valued multivariate measures of forecast accuracy are used in the literature. In this paper, I use the log determinant statistic $\log|\Omega_M(h)|$ and the trace statistic $\text{tr}|\Omega_M(h)|$. I set M equal to a diagonal matrix with the sample variances of the time series based on data until 2002:4 as diagonal elements. With M equal to a diagonal matrix, the trace statistic reduces to a simple weighted average of the RMSEs of the individual series.

I also evaluate the accuracy of density forecasts of the competing models. For that purpose, I use the log predictive predictive density score test of multivariate forecast density. The log predictive density score of the h-step ahead predictive density is

$$S_t(Y_{t+h}) = -2\log p_t(x_{t+h}) \tag{65}$$

where the term $p_t(\cdot)$ denotes the forecast distribution. Under the normality assumption, we have that

$$S_t(Y_{t+h}) = k\log(2\pi) + \log|\Sigma_{t+h|t}| + (Y_{t+h} - \bar{Y}_{t+h|t})'\Sigma_{t+h|t}^{-1}(Y_{t+h} - \bar{Y}_{t+h|t}), \tag{66}$$

with the posterior mean $\bar{Y}_{t+h|t}$ and posterior covariance matrix $\Sigma_{t+h|t}$ of the h-step ahead forecast distribution. The average log predictive density score is

$$S(h) = N_h^{-1} \sum_{t=T}^{T+N_h-1} S_t(Y_{t+h}). \tag{67}$$

7 Results

7.1 Bayesian estimates

The posterior modes from the estimation of the 'benchmark' model outlined earlier are reported in the third column of Table 2.[11] The estimates of the intertemporal elasticity of substitution are closer to the lower range of values used in the business cycle literature (e.g. see Rotemberg ad Woodford, 1992). Households have a degree of habit formation at the mode lower than hat is obtained by Smets and Wouters (2003). The labour supply elasticity is estimated consistently larger than one. The relation between the parameters of the money-bond adjustment costs is consistent with the relation suggested by the theory. Their estimates are of magnitude close to the calibration proposed by Marzo, Söderström and Zagaglia (2008) for the U.S. The estimates of the coefficients in the Taylor rule deliver a high degree of policy inertia, a strong reaction to inflation, and a positive response to output, which is broadly in line with the estimates of citetsw03. The estimated coefficient of the money growth target is statistically significant, thus corroborating the results of Andrés, López-Salido and Vallés (2006). However, it is lower than what the estimates available from the literature. The estimates of the adjustment cost parameters of prices and wages are much higher than those of Kim (2000). The posterior estimates for parameter on the investment adjustment costs can be reconciled with those of Christiano, Eichenbaum, and Evans (2005). Most of the autoregressive shocks have a degree of persistence lower than the prior mean, with the exceptions of the labour supply and investment shocks. Finally, the posterior modes of the standard deviations of the shocks are on average larger than those obtained by Christiano, Motto and Rostagno (2007).

Table 2 also includes the posterior modes for models with flexible prices, no adjustment costs between bonds and money, no consumption habits, and no money growth target in the Taylor rule. Table 3 reports the posterior modes for models without inflation target shock, without money demand shock. The results that there are no major changes to the benchmark posterior modes.

Table 4 details the posterior estimates for the other variants of the benchmark DSGE model. The fourth column reports the posterior modes of the model without money demand feedback. Both the intertemporal elasticity of substitution and the labour supply elasticity are higher than under the benchmark estimates. However the model displays a larger degree of rigidity both in the goods and in the bond markets. The elasticity of money demand is about twice as large as the estimates of Andrés, López-Salido and Vallés (2006). This can be due to a variety of reasons. It should be estimated that the model of Andrés, López-Salido and Vallés (2006) does not include wage frictions, and that it is estimated only using a small number of series and includes four structural shocks.

The fifth column of Table 4 shows the estimates of the New Keynesian model without term structure. This framework is characterized by higher intertemporal elasticity of substitution. This suggests that, by simplifying the portfolio allocation problem and removing frictions, households can use resources in a more flexible way. At the same time, there is a higher degree of habit formation. The estimated labour supply elasticity becomes lower because wages are slightly more flexible, though the degree of indexation to the inflation target rises. From the perspective of the central bank, the estimated response to inflation falls. This happens because price setters face lower adjustment costs

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[11] The validity of the results from Bayesian estimation rests on the convergence of the Markov chain. I check for convergence by monitoring plots of the draws from the Markov chain, and by computing two diagnostic tests. I use the CUSUM test of Bauwens et al. (1999) and the separated partial means tests of Geweke (2005, p. 149). All these criteria indicate that the Markov chain converges without problems.

when changing nominal prices.

The last column of Table 4 includes the estimates of the model of De Graeve, Emiris and Wouters (2009). The results show that the expectations-consistent restrictions cause a number of parameter estimates to change with respect to the benchmark. The parameter on the investment adjustment cost becomes almost six times as large as the benchmark. Furthermore, the estimated shocks are less persistent and more volatile than the benchmark.

7.2 Forecast evaluation

The forecast evaluation statistics are computed by estimating the models until December 2002. The forecast evaluation starts in January 2003. As stressed by Diebold, Piazzesi, and Rudebusch (2005) and Rudebusch, Sack, and Swanson (2007), the challenge of the macro-finance literature consists in modelling jointly the macroeconomy and the term structure of interest rates. Therefore, the forecast evaluation application will focus on both the term structure yields, and the real variables.

Figure 2 plots the root mean squared errors for forecasts up to 12 quarters ahead. The competing models are a VAR(3), a BVAR(3), and a random walk.[12] With respect to macro variables, the DSGE model of the term structure generates the best predictions for inflation and output over all the horizons. Its performance is close to the one of the best model for both consumption and the monetary aggregate. The model does not perform as well for investment, employment and wages. The predictive power of the DSGE model for the bond yields is close to best at the longer horizons, as the VAR models tend to do better for up to 4 months ahead.

Figure 3 reports the root mean squared errors of the versions of the DSGE without various frictions or without exogenous shocks. Several points of interest emerge. The benchmark specification achieves the best predictive performance for most of the variables, with the exception of investment and employment. Removing the money velocity shock, the adjustment costs between bonds and money, or the money target in the Taylor rule worsens the predictive performance for M3. The models without inflation target shock and without price stickiness generate forecast errors larger than those of the benchmark model. However, the decline in predictive performance is rather small. This is somewhat at odds with what the macro-finance literature suggests, which suggests that nominal price rigidities are the key driving forces for bond prices (e.g., see Gurkaynak, Sack and Swanson, 2005 and Emiris, 2006). Taken at face value, this suggests that the models that disregard the feedback might put excessive weight on the role of nominal rigidities for term structure yields.

Figure 4 reports the forecast statistics of the standard New Keynesian model without the term structure. The model with the term structure predicts both output and inflation more accurately than the standard New Keynesian model. This result is of interest especially because the model without the term structure is a good forecasting model as it delivers a good predictive performance with respect to both the random walk and the BVAR. These findings suggest that the modelling strategy for the term structure pursued in this paper generates information for predicting output and inflation that is not contained in the standard model without the term structure.

Figure 5 plots the out-of-sample forecast statistics of the benchmark model and the model without money demand feedback. Two observations arise. First, failing to account for the relation between output and money with an endogenous term structure worsens the misspecification of money demand,

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[12] I use a VAR and a BVAR of order 3 for illustrative purposes. In fact I find that the predictive performance is largely invariant to the order of these models.

which explains the large forecast failure of the model without money demand feedback for M3. Second, the benchmark model predicts the term structure yields better than the model without money feedback. This finding is surprising in light of the fact that the model with money in the utility includes the additional shock to consumption preferences. This allows to discriminate between exogenous variations in consumption and those of money demand, and should provide additional fitting ability. The overall lesson is that the relation between output and money featured in the benchmark model is supported by its forecasting performance.

It is also instructive to compare the predictive performance for M3 of the model without money demand feedback and the standard New Keynesian model of Figure 4. The root mean squared errors in the model without money feedback are twice as large as those of the standard model. This could arise if the modelling strategy for the endogenous term structure was a source of under-fitting. In additional forecasting exercises not reported here, a model with no money demand feedback and no endogenous term structure loses further predictive ability for M3 with respect to a model without feedback and endogenous long-term rates, without major deteriorations in the forecasting ability of the remaining variables. These considerations suggest that the money demand feedback captures relevant features of the monetary transmission mechanism.

Figure 6 plots the out-of-sample forecast statistics for the model De Graeve, Emiris and Wouters (2009). It is evident that the additional restrictions imposed by the expectation-consistent pricing relations create a general deterioration in the predictive power of the model, in particular for output and M3. The pattern of forecast errors for inflation, though, is rather close to the one of the best forecasting model. This explains why the forecasts of the model of De Graeve, Emiris and Wouters (2009) for the money market rate are still acceptable. Overall, these findings indicate that the bond market frictions behind the endogenous term structure of the benchmark model yield desirable empirical properties that cannot be generated by a competing pricing for bonds.

Table 5 reports the multivariate accuracy measures, the log determinant and the trace statistics of the mean squared error matrix for 3 forecast horizons (1, 4 and 12 quarters ahead). For comparison purposes, the forecasts are shown for two sets of variables. The first group of variables, including inflation, output, money and the short-term rate, allows to compare all the models. The second group consists of the three term structure yields. For this case, the DSGE model without long-term rates is excluded from the comparison. The results from multivariate accuracy confirm the findings from the univariate measures on several points. The BVAR is the best predictive model both for the real variables and for the term structure yields. The benchmark DSGE performs better than the model variant without frictions, with only one exception. The log predictive density score suggests that the model of De Graeve, Emiris and Wouters (2009) beats the benchmark DSGE only for forecasts of real variables at 1 quarter ahead.

8 Conclusion

A large number of studies investigates the role of monetary policy and, in particular, changes in the central bank's inflation target for the dynamics of government bond yields. With few exceptions, the empirical literature ignores the policymakers' common view that the yield curve is a key part of the monetary transmission mechanism. The available macro-finance models are also been used for forecasting the term structure of interest rates.

In this paper, I use Bayesian techniques to estimate the general equilibrium model of Marzo, Söderström and Zagaglia (2008) where long-term rates affect both real and nominal variables. The theoretical framework is based on the 'theory of preferred habitat' of investors, which characterizes the portfolio allocation problem as a sluggish decision of agents over different market segments. The model includes frictions in the money and bond market to generate equilibrium holdings of several bonds. Following the approach of Adolfson, Lindé and Villani (2007), I then study the univariate predictive performance by comparing several forecast accuracy measures across different DSGE models.

The results show that the model presented in this paper compares favorably with respect to unrestricted models (VAR and BVAR) for predicting both real and nominal variables, including the term structure yields. The model also fares well in comparison with the DSGE model of the term structure of De Graeve, Emiris and Wouters (2009), where long-term rates are priced consistently with the expectations hypothesis. These findings suggest that the model of the feedback from the term structure captures relevant properties of the data, thus generating superior out-of-sample forecasts.

Numerous extensions to the current analysis can be envisaged. In a work in progress, I relax the assumption on the information set that is currently used in the estimation of the benchmark DSGE model. In particular, I employ a large panel dataset with macroeconomic and bond yield data along the lines of Boivin and Giannoni (2006). This suggests that it would be interesting to enlarge the range of competing models by including the no-arbitrage factor VAR of Moench (2008). An additional dimension of interest is the misspecification of the benchmark DSGE. In this sense, I am planning to apply the methods proposed by Del Negro and Schorfheide (2004).

A Loglinearization

A.1 Households

$$\begin{aligned}
&\frac{\gamma}{\sigma}(1-\gamma)^{-1/\sigma-1}c\hat{c}_{t-1}-\left[\frac{1}{\sigma}\left(1+\beta\gamma^2\right)(1-\gamma)^{-1/\sigma-1}+3\lambda\epsilon^m\left(\frac{c}{m}\right)^2\right]\hat{c}_t\\
&\qquad+\frac{\gamma}{\sigma}\beta(1-\gamma)^{-1/\sigma-1}E_t\hat{c}_{t+1}=\left(1+\epsilon^m\frac{c}{m^2}\right)\lambda\hat{\lambda}_t-3\lambda\epsilon^m\left(\frac{c}{m}\right)^2\hat{m}_t+\frac{3}{2}\lambda\epsilon^m\left(\frac{c}{m}\right)^2\hat{\epsilon}^m_t
\end{aligned}\tag{A1}$$

$$\begin{aligned}
&\Psi\frac{\theta_\ell}{w}\ell^{1/\psi}\hat{\epsilon}^\ell_t+\left(\Psi\frac{\theta_\ell}{w}\ell^{1/\psi}-\lambda\theta_\ell\ell\right)\hat{\theta}_{\ell,t}+\left[(1+1/\psi)\frac{\theta_\ell}{w}\ell^{1/\psi}+\lambda(1-\theta_\ell)\ell\right]\hat{\ell}_t\\
&-\left[\psi\frac{\theta_\ell}{w}\ell^{1/\psi}+\lambda\phi_w\pi^2(1+\gamma_w)-\lambda\phi_w\gamma_w\pi^*\pi-\beta\lambda\phi_w(1+2\gamma_w)-2\beta\lambda\phi_w\pi^*\pi\right]\hat{w}_t\\
&-\lambda\left[\phi_w\gamma_w\pi(\pi-\pi^*)-(1-\theta_\ell)\ell\right]\hat{\lambda}_t\\
&+\lambda\phi_w\gamma_w\pi^*\pi\hat{\pi}^*_t-\left[\lambda\phi_w\left(\pi^*(1+\gamma_w)-\gamma_w\pi^*\pi\right)-\beta\lambda\phi_w(1-\gamma_w)\pi^2\right]\hat{\pi}_t\\
&+\beta\phi_w\lambda\phi_w\pi^*\pi E_t\hat{\pi}^*_{t+1}+\lambda\phi_w\left(\pi^2(1+\gamma_w)-\gamma_w\pi^*\pi\right)\hat{w}_{t-1}+\lambda\phi_w(1-\gamma_w)\pi^2\hat{\pi}_{t-1}\\
&+\beta\phi_w\lambda\gamma_w(\pi-\pi^*)\hat{\lambda}_{t-1}+\beta\lambda\phi_w\gamma_w\pi(\pi-\pi^*)E_t\hat{\lambda}_{t+1}\\
&\qquad+\beta\lambda\phi_w\left[(1+2\gamma_w)\pi^2-2\gamma_w\pi^*\pi\right]E_t\hat{w}_{t+1}+\beta\lambda\phi_w\left[(1+\gamma_w)\pi^2-\gamma_w\pi^*\pi\right]E_t\hat{\pi}_{t+1}
\end{aligned}\tag{A2}$$

$$\begin{aligned}
&\frac{\beta}{\pi}\lambda E_t\hat{\lambda}_{t+1}-\frac{\beta}{\pi}\lambda E_t\hat{\pi}_{t+1}=\left[3\epsilon^m\left(\frac{c}{m}\right)^3+(v_M+v_L)\lambda y\right]\hat{m}_t\\
&\qquad+\lambda\hat{\lambda}_t-3\epsilon^m\left(\frac{c}{m}\right)^3\hat{c}_t-v_M\lambda\frac{y}{m}\hat{b}_{M,t}-v_L\lambda\frac{y}{m}\hat{b}_{L,t}-\epsilon^m\left(\frac{c}{m}\right)^3\hat{\epsilon}^m_t
\end{aligned}\tag{A3}$$

$$\hat{R}_t+E_t\hat{\lambda}_{t+1}-E_t\hat{\pi}_{t+1}=\hat{\lambda}_t\tag{A4}$$

$$\begin{aligned}
&\beta\frac{R_M}{\pi}\lambda\hat{R}_{M,t}+\beta\lambda\left(\frac{R_M}{\pi}+\phi_S y\right)E_t\hat{\lambda}_{t+1}-\beta\frac{R_M}{\pi}\lambda E_t\hat{\pi}_{t+1}\\
&\quad+\beta\phi_S\lambda yE_t\hat{y}_{t+1}+3\beta\phi_S\lambda yE_t\hat{b}_{S,t+1}=\\
&\quad\lambda\left(1+\frac{3}{2}\phi_S y\right)\hat{\lambda}_t+\frac{3}{2}\lambda\phi_S y\hat{y}_t-3\phi_S\lambda y\hat{b}_{M,t-1}\\
&\qquad+\left[3\phi_S\lambda y(1+\beta)-\lambda v_M y\frac{m}{b_M}\right]\hat{b}_{M,t}+\lambda v_M\frac{m}{b_M}y\hat{m}_t
\end{aligned}\tag{A5}$$

$$\begin{aligned}
&\beta\frac{R_L}{\pi}\lambda\hat{R}_{L,t}+\beta\lambda\left(\frac{R_L}{\pi}+\phi_L y\right)E_t\hat{\lambda}_{t+1}-\beta\frac{R_L}{\pi}\lambda E_t\hat{\pi}_{t+1}\\
&\quad+\beta\phi_L\lambda yE_t\hat{y}_{t+1}+3\beta\phi_L\lambda yE_t\hat{b}_{L,t+1}=\\
&\quad\lambda\left(1+\frac{3}{2}\phi_L y\right)\hat{\lambda}_t+\frac{3}{2}\lambda\phi_L y\hat{y}_t-3\phi_L\lambda y\hat{b}_{L,t-1}\\
&\qquad+\left[3\phi_L\lambda y(1+\beta)-\lambda v_L y\frac{m}{b_L}\right]\hat{b}_{L,t}+\lambda v_L\frac{m}{b_L}y\hat{m}_t
\end{aligned}\tag{A6}$$

$$\beta(1-\delta)\mu E_t\hat{\mu}_{t+1} = \mu\hat{\mu}_t - \lambda q\hat{\lambda}_t - \lambda q\hat{q}_t \tag{A7}$$

$$\begin{aligned}\beta\mu\phi_K E_t\hat{\mu}_{t+1} + 3\beta\mu\phi_K E_t\hat{i}_{t+1} = \lambda\hat{\lambda}_t + \mu\left(\frac{3}{2}\phi_K + 1\right)\hat{\mu}_t \\ + \mu\left(\frac{3}{2}\phi_K + 1\right)\hat{\epsilon}^i_t + \mu\phi_K(3+\beta)\hat{i}_t - 3\mu\phi_K\hat{i}_{t-1}\end{aligned} \tag{A8}$$

$$\hat{e}_t = \beta E_t\hat{e}_{t+1} + \frac{(1-\beta\xi_e)(1-\xi_e)}{\xi_e}\left(\hat{\ell}_t - \hat{e}_t\right) \tag{A9}$$

A.2 Firms

$$\hat{y}_t = \frac{y+\Phi}{y}\left[\hat{\epsilon}^a_t + \alpha\hat{k}_t + (1-\alpha)\hat{\ell}_t\right] \tag{A10}$$

$$\begin{aligned}&(\mathrm{mc}-1)\,\theta_f\hat{\theta}_{f,t} + (\theta_f\mathrm{mc})\,\hat{\mathrm{mc}}_t + \beta\phi_P\gamma_P\left(\pi-\pi^*\right)\pi E_t\hat{\lambda}_{t+1} \\ &- \beta\phi_P\gamma_P\left(\pi-\pi^*\right)\pi\hat{\lambda}_t + \beta\phi_P\gamma_P\left(\pi-\pi^*\right)\pi E_t\hat{y}_{t+1} - \beta\phi_P\gamma_P\left(\pi-\pi^*\right)\pi\hat{y}_t \\ &- \beta\phi_P\gamma_P\pi\pi^* E_t\hat{\pi}^*_{t+1} + \beta\phi_P\left[\pi^2(1+\gamma_P) - 2\gamma_P\pi\pi^*\right]E_t\hat{\pi}_{t+1} \\ &\qquad = \phi_P\left(\pi^2\left(1+\gamma_P\right) - \gamma_P\pi^*\pi + \beta(1-\gamma_P)\pi^2\right)\hat{\pi}_t + \phi_P\pi\pi^*\hat{\pi}^*_t - \phi_P(1-\gamma_P)\pi^2\hat{\pi}_{t-1}\end{aligned} \tag{A11}$$

$$\hat{w}_t = \hat{\mathrm{mc}}_t + \frac{y}{y+\Phi}\hat{y}_t - \hat{\ell}_t \tag{A12}$$

$$q\hat{q}_t = \alpha\left(\frac{y+\Phi}{k}\mathrm{mc}\right)\hat{\mathrm{mc}}_t + \alpha\left(\frac{y}{k}\mathrm{mc}\right)\hat{y}_t - \alpha\left(\frac{y+\Phi}{k}\mathrm{mc}\right)\hat{k}_t \tag{A13}$$

$$\hat{w}_t + \hat{\ell}_t = \hat{q}_t + \hat{k}_t \tag{A14}$$

A.3 Government and central bank

$$h\hat{h}_t = Rb\hat{R}_t + Rb\hat{b}_t + R_Mb_M\hat{R}_{M,t} + R_Mb_M\hat{b}_{M,t} + R_Lb_L\hat{R}_{L,t} + R_Lb_L\hat{b}_{L,t} + m\hat{m}_t \tag{A15}$$

$$T\hat{T}_t = \psi_1 h\hat{h}_{t-1} \tag{A16}$$

$$\begin{aligned}&b\hat{b}_t + b_M\hat{b}_{M,t} + b_L\hat{b}_{L,t} + m\hat{m}_t = \\ &\frac{R}{\pi}b\hat{R}_{t-1} + \frac{R}{\pi}b\hat{b}_{t-1} - \frac{R}{\pi}b\hat{\pi}_t + \frac{R_M}{\pi}b_M\hat{R}_{M,t-1} + \frac{R_M}{\pi}b_M\hat{b}_{M,t-1} - \frac{R_M}{\pi}b_M\hat{\pi}_t \\ &\qquad + \frac{R_L}{\pi}b_L\hat{R}_{L,t-1} + \frac{R_L}{\pi}b_L\hat{b}_{L,t-1} - \frac{R_L}{\pi}b_L\hat{\pi}_t + \frac{m}{\pi}\hat{m}_{t-1} - \frac{m}{\pi}\hat{\pi}_t + g\hat{g}_t - \tau\hat{\tau}_t\end{aligned} \tag{A17}$$

$$\hat{R}_t = \alpha_R\hat{R}_{t-1} + (1-\alpha_R)\left[\hat{\pi}^*_t + \alpha_\pi\left(\hat{\pi}_t - \hat{\pi}^*_t\right) + \alpha_y\hat{y}_t + \alpha_m\left(\hat{m}_t - \hat{m}_{t-1} + \pi_t\right)\right] + \epsilon^R_t \tag{A18}$$

A.4 Resource constraint

$$\left(1 - b_M\frac{\phi_S}{2} - b_L\frac{\phi_L}{2}\right) y\hat{y}_t = \left[1 + \frac{3}{2}\epsilon^m\left(\frac{c}{m}\right)^2\right] c\hat{c}_t + i\hat{i}_t + g\hat{g}_t$$
$$+ (\phi_S y)b_M\hat{b}_{M,t-1} + (\phi_L y)b_L\hat{b}_{L,t-1} + \frac{3}{2}(\phi_S y)b_M\hat{b}_{M,t} + \frac{3}{2}(\phi_L y)b_L\hat{b}_{L,t}$$
$$- \epsilon^m\left(\frac{c}{m}\right)^3 m\hat{m}_t + \frac{c}{2}\left(\frac{c}{m}\right)^2\epsilon^m\hat{\epsilon}^m_t \quad \text{(A19)}$$

$$k\hat{k}_{t+1} = \left[1 - \frac{\phi_K}{2}\right] i\hat{\epsilon}^i_t + \left[1 - \frac{3}{2}\phi_K\right] i\hat{i}_t + (1-\delta)k\hat{k}_t + \frac{\phi_K}{2} i\hat{i}_{t-1} \quad \text{(A20)}$$

A.5 Exogenous variables and shocks

$$\ln(\epsilon^m_t/\epsilon^m) = \rho_m \ln(\epsilon^m_{t-1}/\epsilon^m) + \nu^m_t \quad \text{(A21)}$$
$$\ln(\epsilon^\ell_t) = \rho_\ell \ln(\epsilon^\ell_{t-1}) + \nu^\ell_t \quad \text{(A22)}$$
$$\ln(\epsilon^i_t) = \rho_i \ln(\epsilon^i_{t-1}) + \nu^i_t \quad \text{(A23)}$$
$$\ln\left(\epsilon^a_t/\epsilon^a\right) = \rho_a \ln\left(\epsilon^a_{t-1}/\epsilon^a\right) + \nu^a_t \quad \text{(A24)}$$
$$\ln(\epsilon^w_t) = \rho_w \ln(\epsilon^w_{t-1}) + \nu^w_t \quad \text{(A25)}$$
$$\ln(\epsilon^P_t) = \rho_P \ln(\epsilon^P_{t-1}) + \nu^P_t \quad \text{(A26)}$$
$$\ln\left(b_{M,t}/b_S\right) = \rho_M \ln\left(b_{M,t-1}/b_S\right) + \nu^S_t \quad \text{(A27)}$$
$$\ln\left(b_{L,t}/b_L\right) = \rho_L \ln\left(b_{L,t-1}/b_L\right) + \nu^L_t \quad \text{(A28)}$$
$$\ln\left(g_t/g\right) = \rho_g \ln\left(g_{t-1}/g\right) + \nu^g_t \quad \text{(A29)}$$
$$\ln\left(\pi^*_t/\pi\right) = \rho_\pi \ln\left(\pi^*_{t-1}/\pi\right) + \nu^\pi_t \quad \text{(A30)}$$
$$\ln(\epsilon^R_t) = \rho_R \ln(\epsilon^R_{t-1}) + \nu^R_t \quad \text{(A31)}$$

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B The steady state

The computation of the deterministic steady state takes as given the values for θ, α, ϕ_P, γ, c/y, $b/\tilde{b}$, $b_S/\tilde{b}$, $b_L/\tilde{b}$, k/y, y, ℓ, ψ, σ, δ, π, R, R_M, and R_L, with total public debt $\tilde{b}$. I normalize all variables with respect to aggregate income y, whose steady-state value equals average output from the dataset.

From the first-order condition for consumption in equation (20), I recover the steady-state value of λ as

$$\lambda = \frac{(1-\gamma\beta)\left[(1-\gamma)\,c\right]^{-\frac{1}{\sigma}}}{1 + \frac{3}{2}\epsilon^m\left(\frac{c}{m}\right)^2}. \quad \text{(B1)}$$

Using the steady-state inflation rate π and the policy rate R, I recover the value of the discount rate from equation (22).

From the optimality condition for labor in (21), I calibrate the parameter and Ψ consistently with a steady-state ratio of market to non-market activities

$$\Psi = \frac{\theta_\ell - 1}{\theta_\ell}\lambda\frac{w}{(\ell)^{1/\psi}}. \quad \text{(B2)}$$

The steady-state level of wage is directly obtained from the firm's first-order condition for labor in equation (32).

From the firm's optimality conditions for labor and the product exhaustion theorem, I obtain

$$\begin{aligned} y &= qk + w\ell \\ &= \left(1-\frac{1}{\theta}\right)(y+\Phi) \\ &= \left(1-\frac{1}{\theta}\right)\epsilon^{a}(k)^{\alpha}(\ell)^{1-\alpha}. \end{aligned} \tag{B3}$$

To ensure zero profits, the fixed cost Φ is set to

$$\Phi = \left(1-\alpha\frac{\theta-1}{\theta}\right)\epsilon^{a}(k)^{\alpha}(\ell)^{1-\alpha}. \tag{B4}$$

Thus, given ℓ and the steady state level of y, I can recover the steady-state level of the technology shock ϵ^{a} from equation (B3).

From the money demand equation 24 and the first-order condition for consumption in equation (20), I solve for ϵ^{m} by choosing the positive root of the resulting second-order equation.

The aggregate resource constraint 42 can be written as a function of the the shares of consumption S_c, investment S_i, government spending S_g and bond-adjustment costs S_b as a fraction of output

$$S_c\left[1+f(v)\right]+S_i+S_g+S_b=1. \tag{B5}$$

From this expression, I calibrate the steady-state share of government spending.

I calibrate the bond adjustment costs to preserve the differences between the yields at the deterministic steady state. Indexing the first-order conditions with respect to short-term bonds B_S and B_L, I have

$$\beta\lambda\frac{R_\iota}{\pi}+\beta\lambda\phi_\iota Y=\lambda\left[1+\frac{3}{2}\phi_\iota Y\right]. \tag{B6}$$

with $\iota = M, L$. From (B6) I observe that bond adjustment costs are non-zero at the steady state, and they are a function of aggregate output. To understand the role of transaction costs, I substitute equation (B6) into the steady-state version of (22). After rearranging, I get

$$\frac{R_\iota}{R}=1+\phi_\iota Y\left(\frac{3}{2}-\beta\right), \tag{B7}$$

and the spread between yield R_ι and R can be rewritten as

$$\frac{R_\iota-R}{R}=\phi_\iota Y\left(\frac{3}{2}-\beta\right). \tag{B8}$$

Equation (B8) identifies the spread existing between the yield on bond ι and the federal funds rate as a function of each bond adjustment cost. From (B7), I can calibrate ϕ_ι according to

$$\phi_\iota=\frac{\beta R_\iota/\pi-1}{Y\left(3/2-\beta\right)}. \tag{B9}$$

The final step of the steady-state parametrization concerns the capital stock and investment. The shadow value of capital accumulation follows from 26

$$\mu=\lambda/\left[1+\beta\phi_K-\frac{3}{2}\phi_K\right], \tag{B10}$$

Equation 25 gives the rental rate of capital

$$q=\left[1-\beta(1-\delta)\right]\frac{\mu}{\lambda} \tag{B11}$$

The steady-state value for the capital stock is obtained from the definition of the output share of capital income

$$k = \alpha \frac{y}{q}. \tag{B12}$$

A similar relation holds for long-run wages

$$w = (1 - \alpha) \frac{y}{\ell}. \tag{B13}$$

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Figure 1: Data series

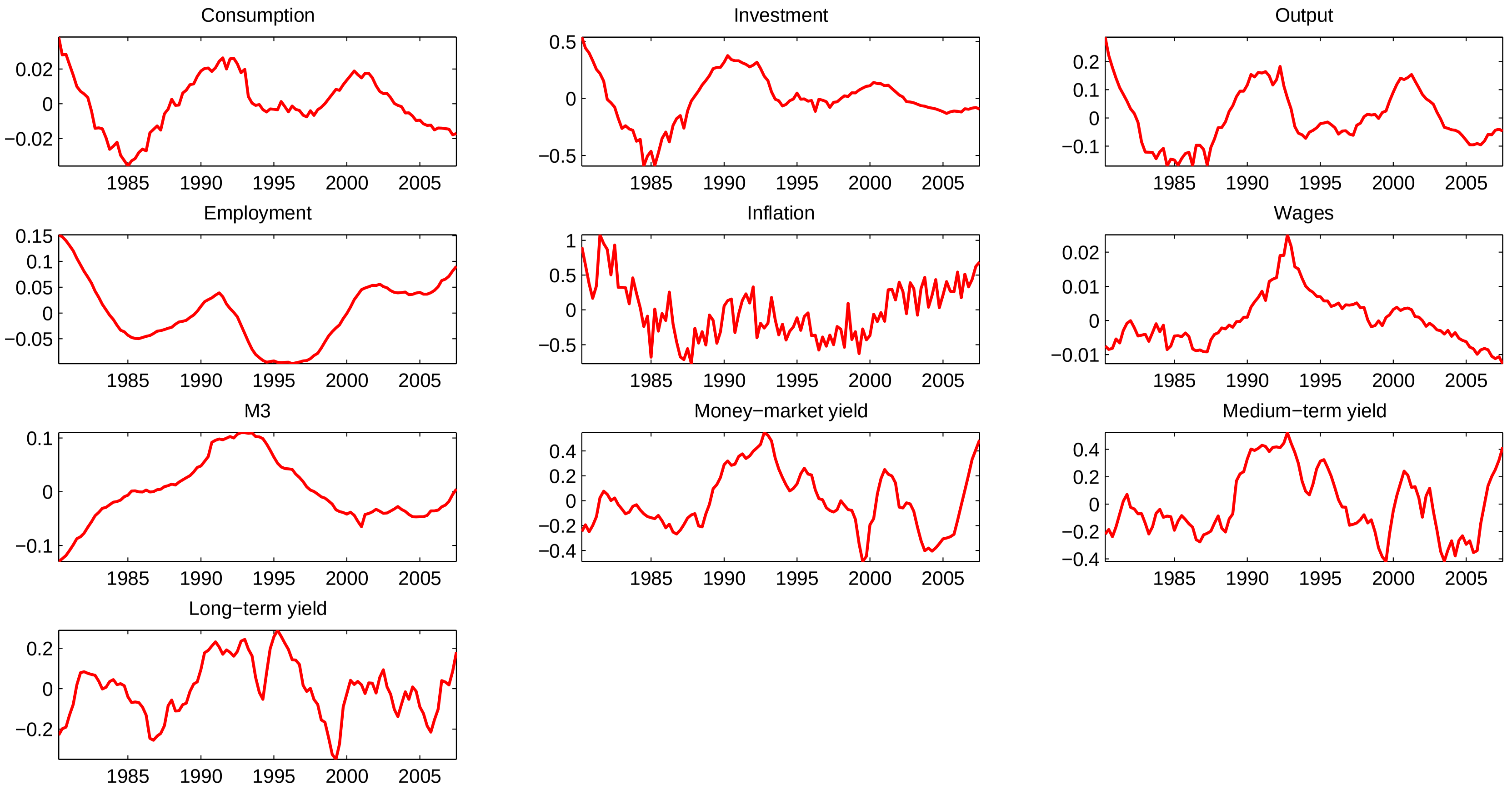

Figure 2: Out-of-sample forecast performance: VAR models vs DSGE

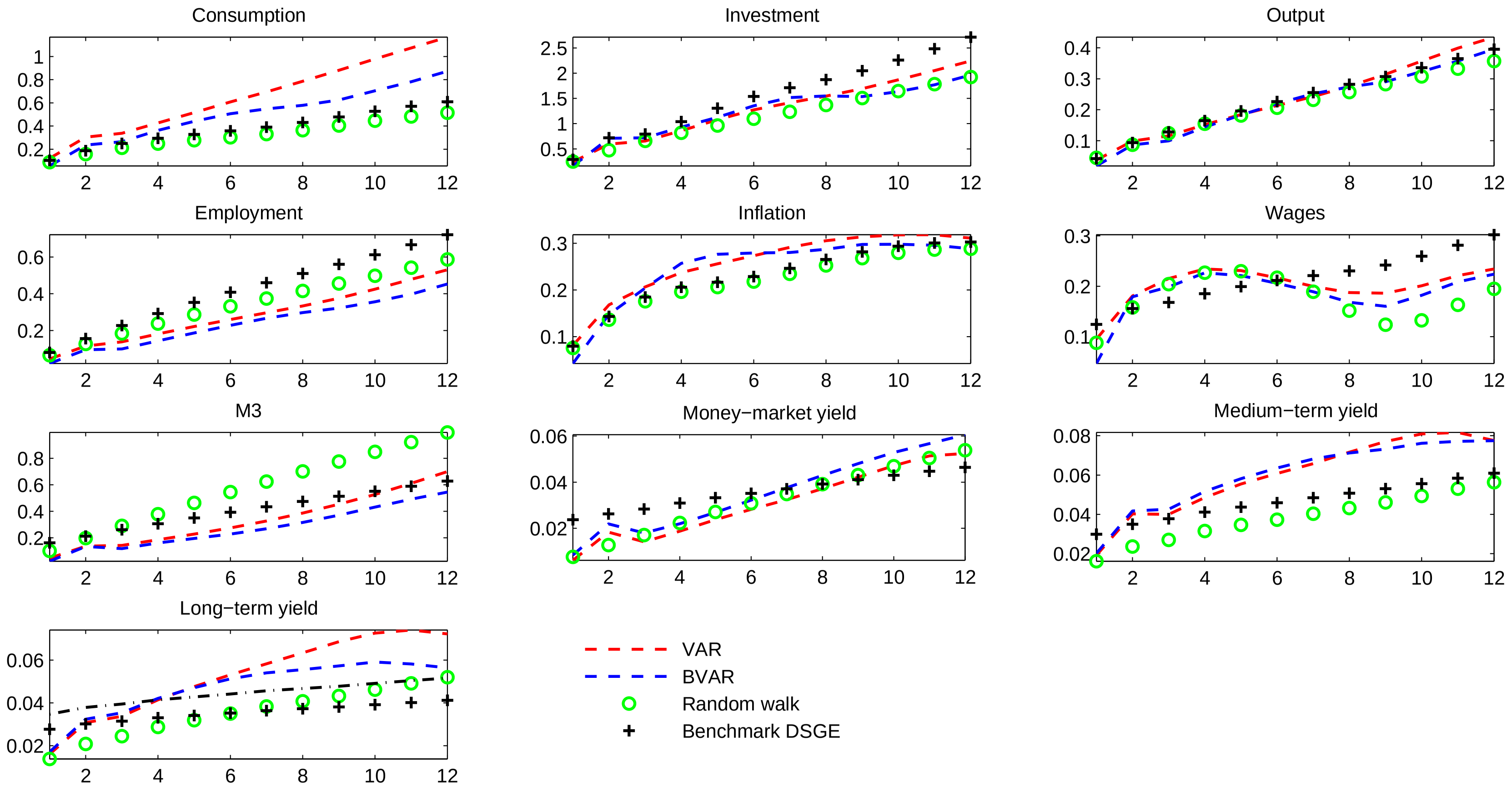

Figure 3: Out-of-sample forecast performance: alternative versions of the DSGE

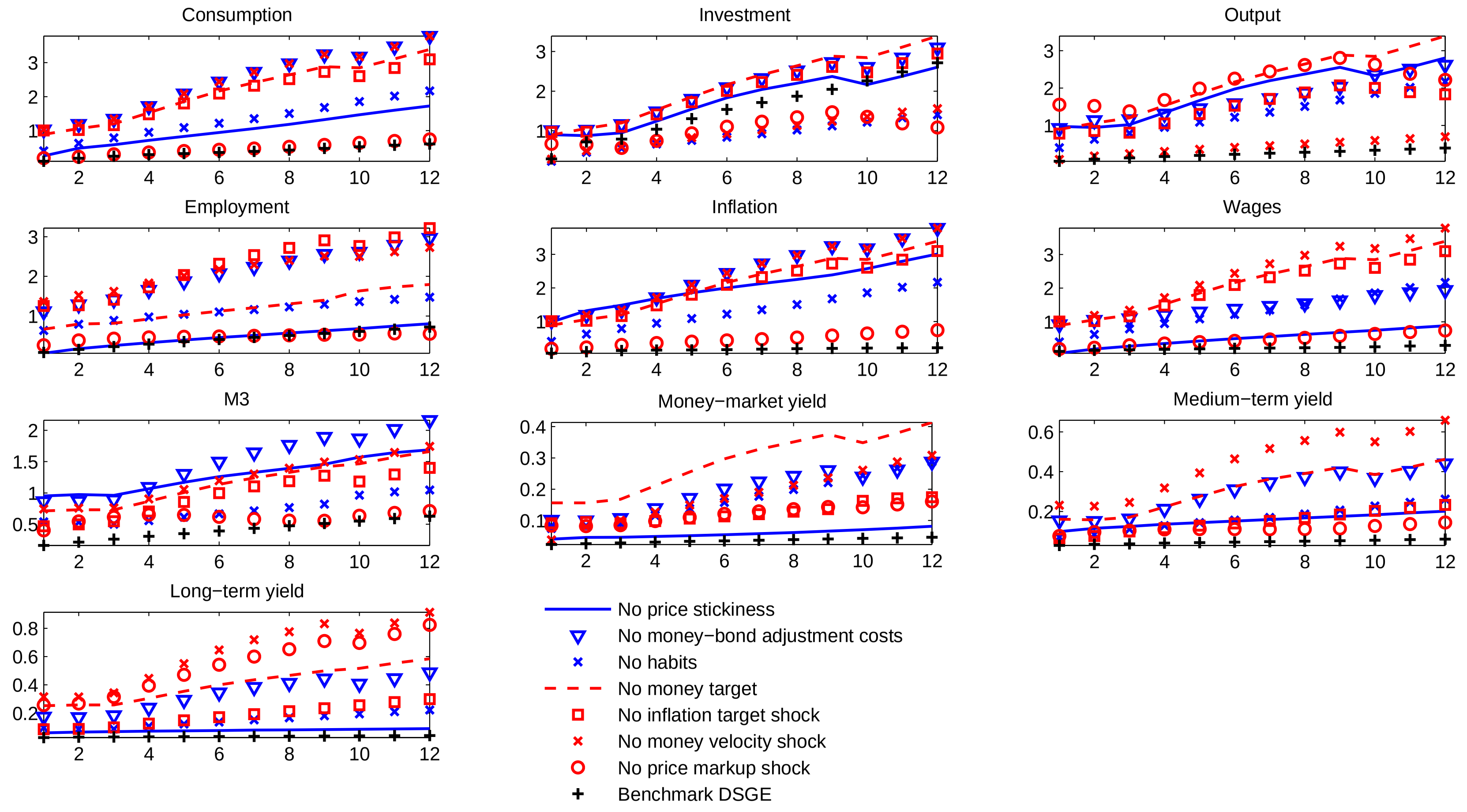

Figure 4: Out-of-sample forecast performance: standard New Keynesian model vs benchmark DSGE

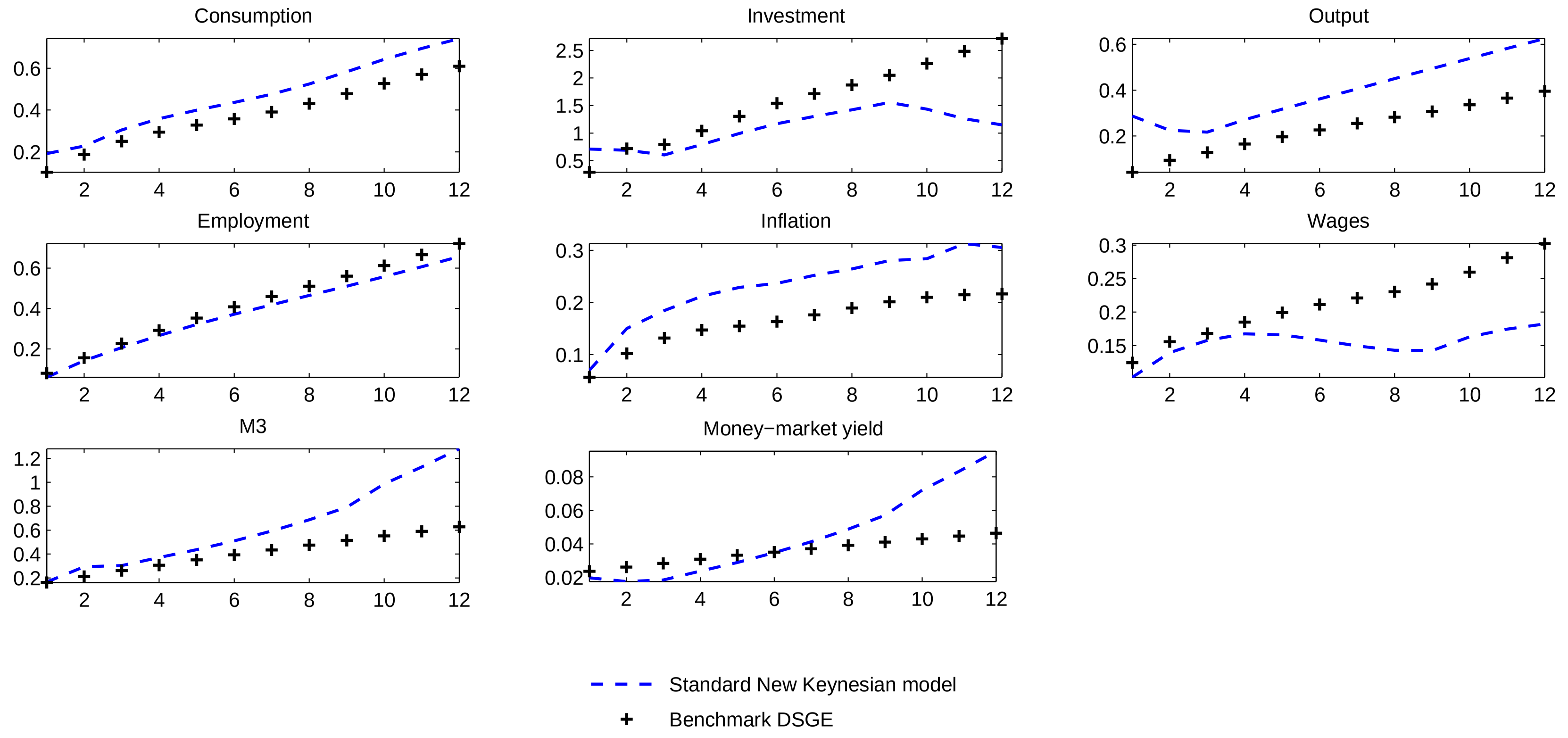

Figure 5: Out-of-sample forecast performance: no money feedback vs benchmark DSGE

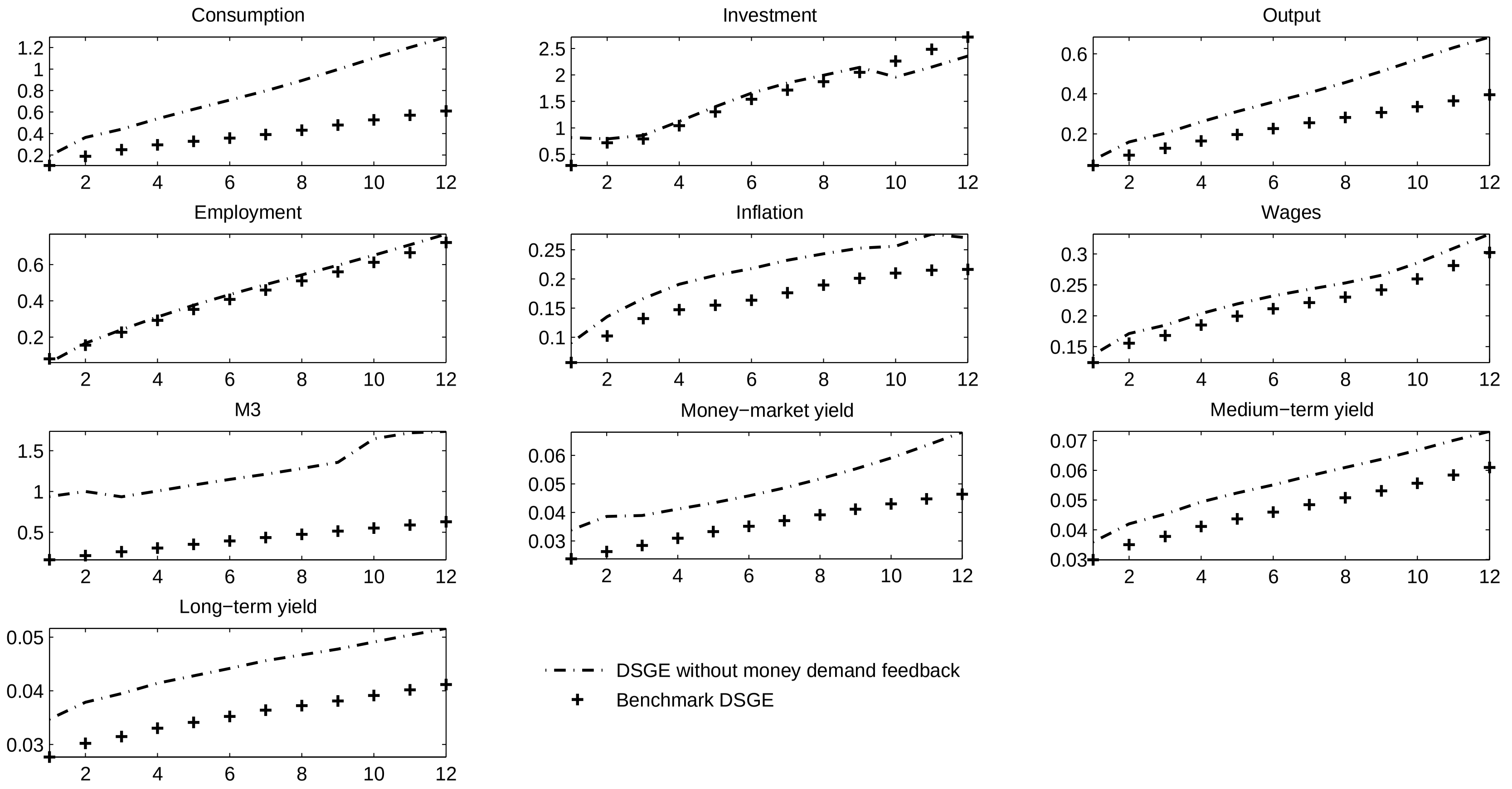

Figure 6: Out-of-sample forecast performance: De Graeve, Emiris and Wouters (2009) vs benchmark DSGE

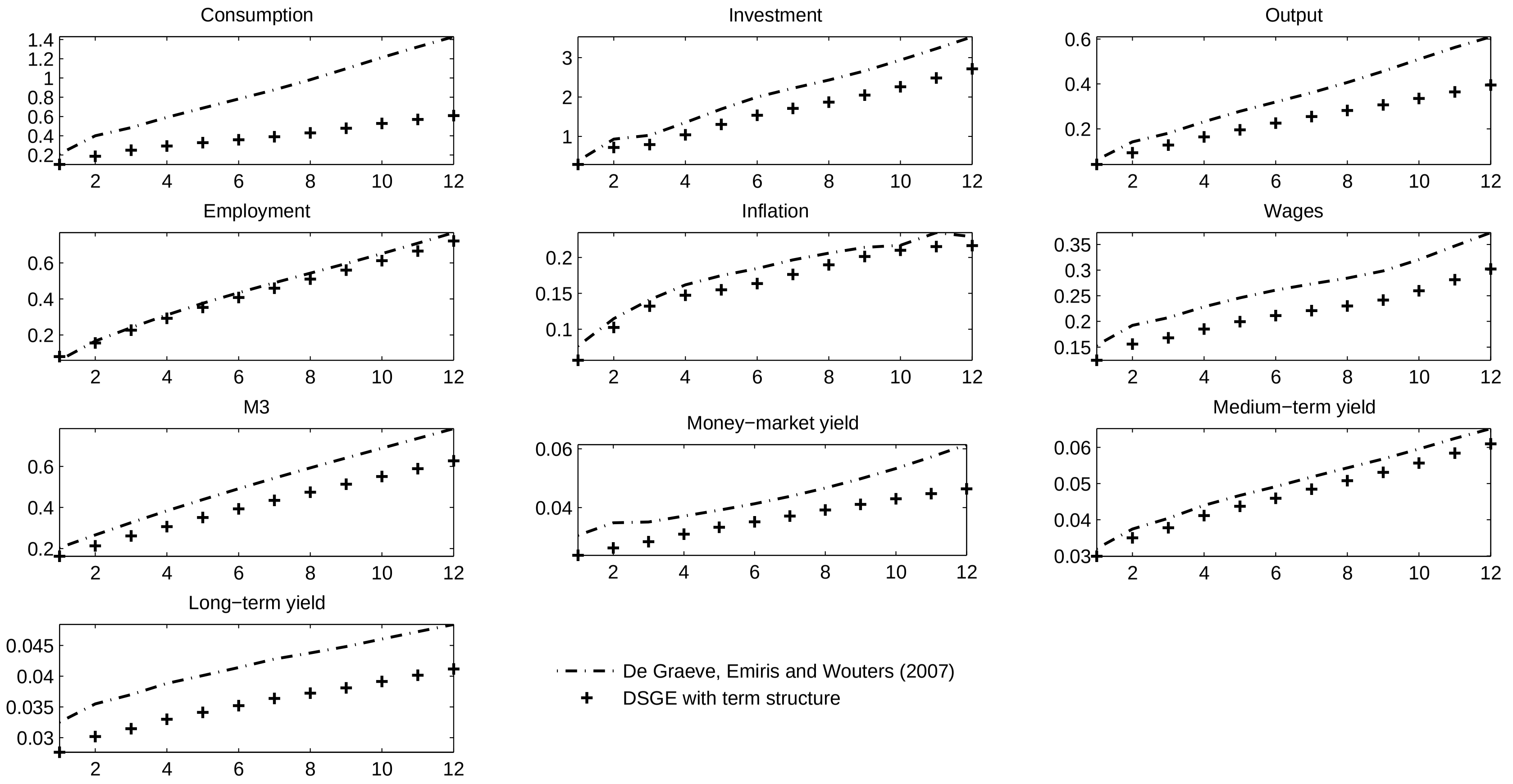

Table 1: Calibrated parameters

Description	Notation	Value
Consumption-GDP ratio	c/y	0.64
Real money/output ratio	m/y	0.66
Ratio of market to non-market activities	$\ell/(1-\ell)$	0.3
Debt-GDP ratio	$(b+b_M+b_L)/y$	0.69
Fraction of short-term debt	b/y	0.201
Fraction of medium-term debt	b_M/y	0.305
Fraction of long-term debt	b_L/y	0.494
Gross money-market rate	R	1.0082
Gross medium-term rate	R_M	1.0112
Gross long-term rate	R_L	1.0130
Preferences and technology		
Discount factor	β	0.992
Steady-state price markup	$(\theta_f-1)/\theta_f$	1.2
Steady-state wage markup	$(\theta_\ell-1)/\theta_\ell$	1.05
Capital depreciation rate	δ	0.025
Share of capital in production	α	0.36
Fixed cost	Φ	7.51
Bond adjustment costs		
Medium-term bond adjustment cost	ϕ_M	0.0009
Long-term bond adjustment cost	ϕ_L	0.0014
Fiscal policy		
Fiscal policy response to nominal liabilities	ψ_1	0.85

Table 2: Estimation results of the benchmark model and its variants (1)

Description	Notation	**Prior distribution**	**Posterior mode**				
			Benchmark	No price stick. ($\phi_P = 0.001$)	No bond-adj. costs ($v_M = v_L = 0$)	No habits ($h = 0$)	No money target ($\alpha_m = 0$)
Preferences and technology							
Intertemp. elast. of subst.	σ	Normal (1,0.4)	0.411	0.430	0.511	0.351	0.382
Habit formation	γ	Beta (0.6,0.2)	0.488	0.472	0.518	0	0.551
Labor supply elast.	ψ	Normal (2,0.75)	1.649	1.921	1.680	1.771	1.691
Adjust. cost of invest.	ϕ_K	Normal (1.5,0.9)	1.223	1.340	1.491	1.350	1.250
Price adjustment cost	ϕ_P	Normal (90,8)	97.490	0.001	92.455	104.621	99.126
Price indexation	γ_P	Beta (0.5,0.2)	0.625	0.566	0.692	0.717	0.704
Wage adjustment cost	ϕ_W	Normal (55,8)	59.730	55.901	57.917	58.033	62.140
Wage indexation	γ_W	Beta (0.5,0.15)	0.177	0.130	0.090	0.277	0.259
Bond adjustment costs							
Money/medium-term bond	v_M	Normal (4,2)	2.209	2.720	0	2.602	2.802
Money/long-term bond	v_L	Normal (2,0.85)	0.385	0.399	0	0.411	0.406
Monetary policy							
M. p. response to inflation	α_π	Normal (2,0.9)	1.794	1.611	1.709	1.604	1.816
M. p. response to output	α_y	Normal (0.15,0.2)	0.302	0.049	0.228	0.201	0.409
M. p. response to money gr.	α_m	Beta (0.5,0.3)	0.197	0.270	0.160	0.230	0
M. p. inertia	α_R	Beta (0.5,0.2)	0.813	0.600	0.720	0.739	0.731
Autoreg. parameters							
Money velocity	ρ_m	Beta (0.85,0.1)	0.930	0.803	0.909	0.706	0.812
Labour supply	ρ_ℓ	Beta (0.85,0.1)	0.917	0.902	0.831	0.658	0.902
Investment	ρ_i	Beta (0.85,0.1)	0.931	0.930	0.827	0.890	0.905
Technology	ρ_a	Beta (0.85,0.1)	0.925	0.927	0.849	0.811	0.899
Price markup	ρ_P	Beta (0.85,0.1)	0.961	0.980	0.850	0.370	0.947
Wage markup	ρ_w	Beta (0.85,0.1)	0.912	0.949	0.897	0.417	0.941
Gov. spending	ρ_g	Beta (0.85,0.1)	0.951	0.858	0.972	0.911	0.873
Med.-term bond sup.	ρ_M	Beta (0.85,0.1)	0.909	0.914	0.899	0.917	0.885
Long-term bond sup.	ρ_L	Beta (0.85,0.1)	0.970	0.939	0.916	0.901	0.890
Monetary Policy	ρ_R	Beta (0.85,0.1)	0.919	0.926	0.827	0.919	0.901
Inflation target	ρ_π	Beta (0.85,0.1)	0.941	0.871	0.815	0.886	0.891
Standard dev.							
Money velocity	σ_m	Inv. Gamma (0.5,2)	0.297	0.317	0.381	0.351	0.318
Labour supply	σ_ℓ	Inv. Gamma (0.3,2)	0.191	0.195	0.180	0.174	0.161
Investment	σ_i	Inv. Gamma (0.4,2)	0.273	0.290	0.226	0.301	0.317
Technology	σ_a	Inv. Gamma (0.2,2)	0.154	0.211	0.211	0.161	0.144
Price markup	σ_P	Inv. Gamma (0.2,2)	0.295	0.404	0.337	0.315	0.304
Wage markup	σ_w	Inv. Gamma (0.2,2)	0.360	0.365	0.275	0.411	0.409
Gov. spending	σ_g	Inv. Gamma (0.4,2)	0.240	0.254	0.152	0.244	0.267
Med.-term bond sup.	σ_M	Inv. Gamma (0.4,2)	0.095	0.079	0.102	0.119	0.105
Long-term bond sup.	σ_L	Inv. Gamma (0.4,2)	0.077	0.070	0.091	0.087	0.093
Monetary policy	σ_R	Inv. Gamma (0.3,2)	0.136	0.139	0.145	0.155	0.119
Inflation target	σ_π	Inv. Gamma (0.2,2)	0.083	0.062	0.090	0.047	0.077
Log marginal likelihood			-410.720	-471.003	-499.120	-431.599	-451.029

Table 3: Estimation results of the benchmark model and its variants (2)

Description	Notation	Posterior mode			
		Benchmark	No infl. target ($\sigma_\pi = 0.0001$)	No money velocity ($\sigma_M = 0.0001$)	No price markup ($\sigma_P = 0$)
Preferences and technology					
Intertemp. elast. of subst.	σ	0.411	0.457	0.430	0.512
Habit formation	γ	0.488	0.411	0.489	0.519
Labor supply elast.	ψ	1.649	1.710	1.899	2.117
Adjust. cost of invest.	ϕ_K	1.223	1.379	1.114	1.901
Price adjustment cost	ϕ_P	97.490	92.800	96.415	91.331
Price indexation	γ_P	0.625	0.513	0.581	0.740
Wage adjustment cost	ϕ_W	59.730	57.394	57.104	58.991
Wage indexation	γ_W	0.177	0.208	0.230	0.068
Bond adjustment costs					
Money/medium-term bond	v_M	2.209	3.228	2.102	3.591
Money/long-term bond	v_L	0.385	0.507	0.258	0.731
Monetary policy					
M. p. response to inflation	α_π	1.794	1.917	1.705	1.619
M. p. response to output	α_y	0.302	0.439	0.315	0.297
M. p. response to money gr.	α_m	0.197	0.311	0.128	0.173
M. p. inertia	α_R	0.813	0.790	0.699	0.741
Autoreg. parameters					
Money velocity	ρ_m	0.930	0.831	0.760	0.724
Labour supply	ρ_ℓ	0.917	0.907	0.741	0.750
Investment	ρ_i	0.931	0.955	0.878	0.889
Technology	ρ_a	0.925	0.877	0.874	0.869
Price markup	ρ_P	0.961	0.970	0.933	0.949
Wage markup	ρ_w	0.912	0.932	0.930	0.892
Gov. spending	ρ_g	0.951	0.956	0.870	0.861
Med.-term bond sup.	ρ_M	0.909	0.910	0.895	0.893
Long-term bond sup.	ρ_L	0.970	0.972	0.922	0.905
Monetary Policy	ρ_R	0.919	0.930	0.850	0.892
Inflation target	ρ_π	0.941	0.920	0.890	0.869
Standard dev.					
Money velocity	σ_m	0.297	0.299	0.0001	0.280
Labour supply	σ_ℓ	0.182	0.185	0.241	0.189
Investment	σ_i	0.273	0.280	0.340	0.301
Technology	σ_a	0.154	0.199	0.241	0.227
Price markup	σ_P	0.295	0.311	0.340	0
Wage markup	σ_w	0.372	0.370	0.417	0.412
Gov. spending	σ_g	0.240	0.259	0.271	0.296
Med.-term bond sup.	σ_M	0.095	0.099	0.103	0.091
Long-term bond sup.	σ_L	0.077	0.092	0.092	0.090
Monetary policy	σ_R	0.136	0.135	0.110	0.119
Inflation target	σ_π	0.083	0.0001	0.116	0.078
Log marginal likelihood		-410.720	-429.106	-515.495	-553.049

Table 4: Estimation results of the benchmark model and its variants (3)

Description	Notation	Posterior mode			
		Benchmark DSGE	No money demand feed.	No term structure	De Graeve et al. (2009)
Preferences and technology					
Intertemporal elasticity of substitution	σ	0.411	0.425	0.712	0.570
Habit formation	γ	0.488	0.518	0.659	0.513
Elasticity of money demand	χ	-	2.195	-	-
Labor supply elasticity	ψ	1.649	1.681	1.417	1.309
Adjustment cost of investment	ϕ_K	1.223	1.307	6.058	1.291
Price adjustment cost	ϕ_P	97.490	101.417	81.553	99.368
Price indexation	γ_P	0.625	0.627	0.641	0.774
Wage adjustment cost	ϕ_W	59.730	59.769	55.274	67.296
Wage indexation	γ_W	0.177	0.142	0.319	0.208
Bond adjustment costs					
Money/medium-term bond	v_M	2.209	2.925	-	-
Money/long-term bond	v_L	0.385	0.417	-	-
Monetary policy					
Monetary policy response to inflation	α_π	1.794	1.792	1.307	2.101
Monetary policy response to output	α_y	0.302	0.305	0.199	0.263
Monetary policy response to money growth	α_m	0.197	-	0.216	0.237
Monetary policy inertia	α_R	0.813	0.805	0.790	0.769
Autoregressive parameters					
Consumption preference	ρ_p	-	0.520	-	-
Money velocity	ρ_m	0.930	0.738	0.914	0.904
Labour supply	ρ_ℓ	0.917	0.815	0.912	0.850
Investment	ρ_i	0.931	0.931	0.945	0.916
Technology	ρ_a	0.925	0.892	0.933	0.887
Price markup	ρ_P	0.961	0.466	0.870	0.913
Wage markup	ρ_w	0.912	0.512	0.486	0.859
Government spending	ρ_g	0.951	0.301	0.719	0.910
Medium-term bond supply	ρ_M	0.909	0.409	-	-
Long-term bond supply	ρ_L	0.970	0.487	-	-
Monetary Policy	ρ_R	0.919	0.692	0.747	0.885
Inflation target	ρ_π	0.941	0.912	0.885	0.917
Standard deviations					
Consumption preference	σ_p	-		-	-
Money velocity	σ_m	0.297	0.294	0.351	0.217
Labour supply	σ_ℓ	0.182	0.180	0.207	0.114
Investment	σ_i	0.273	0.271	0.294	0.315
Technology	σ_a	0.154	0.155	0.282	0.281
Price markup	σ_P	0.295	0.297	0.391	0.237
Wage markup	σ_w	0.372	0.375	0.416	0.319
Government spending	σ_g	0.240	0.241	0.320	0.228
Medium-term bond supply	σ_M	0.095	0.093	-	-
Long-term bond supply	σ_L	0.077	0.079	-	-
Monetary Policy	σ_R	0.136	0.131	0.101	0.160
Inflation target	σ_π	0.083	0.087	0.055	0.097
Measurement errors					
Std. dev. medium-term yield	σ_M	-	-	-	0.210
Std. dev. long-term yield	σ_L	-	-	-	0.251
Correlation medium-long yields	$\rho_{M,L}$	-	-	-	0.779

Legend: The prior assumptions of the measurement errors are as follows. The standard deviations of both shocks have a uniform prior with mean 1.5 and standard deviation 1.5. The correlation of the measurement errors has a uniform prior with mean 0 and standard deviation 0.8.

Table 5: Multivariate accuracy measures

Model	*Three variables:* π_t, y_t, m_t, R_t			*Term structure:* R_t, $R_{M,t}$, $R_{L,t}$		
1 quarter ahead						
	Log determinant statistics	Trace statistics	LPDS	Log determinant statistics	Trace statistics	LPDS
Benchmark DSGE	-14.626**	1.517***	3.490***	-12.107**	1.217**	2.018**
DSGE with no price stickiness	-13.207	1.539	5.058	-11.331	1.327	2.090***
DSGE with no bond adjustment costs	-13.199	1.520	5.449	11.109	1.316	4.017
DSGE with no habits	-14.051	1.649	6.130	-11.107	1.305	4.197
DSGE with no money target	-14.115	1.992	5.704	-11.124	1.392	2.940
DSGE with no inflation target shock	-13.700	1.715	5.791	-11.704	1.320	3.610
DSGE with no money velocity shock	-13.590	1.790	6.250	-11.511	1.384	3.430
DSGE with no price markup shock	-14.460	1.690	6.559	-11.609	1.379	2.950
DSGE with no money demand feedback	-14.084	1.604	6.401	-11.905***	1.319	3.070
De Graeve, Emiris and Wouters (2009)	-14.280	1.599	3.191**	-11.331	1.299	2.191
VAR	-14.533***	1.492**	4.992	-11.406	1.274***	2.992
BVAR	-15.020*	1.408*	2.701*	-12.952*	0.958*	1.688*
Standard New Keynesian model	-13.619	1.940	4.055	-	-	-
4 quarters ahead						
	Log determinant statistics	Trace statistics	LPDS	Log determinant statistics	Trace statistics	LPDS
Benchmark DSGE	-11.610**	2.697**	15.513*	-12.980**	3.660**	16.910**
DSGE with no price stickiness	-11.207	2.939	17.098	12.005	3.930	20.028
DSGE with no bond adjustment costs	-10.149	2.820	18.009	-12.130	3.829	19.303
DSGE with no habits	-11.051	2.940	18.460	-12.100	3.949	19.996
DSGE with no money target	-11.115	2.992	19.790	-11.139	3.973	21.005
DSGE with no inflation target shock	-10.720	2.811	19.781	-12.759***	3.811	19.799
DSGE with no money velocity shock	-10.595	2.990	19.250	-12.511	3.990	20.319
DSGE with no price markup shock	-9.560	2.995	18.559	-11.530	3.744	20.900
DSGE with no demand feedback	-10.084	2.904	19.419	-12.119	3.904	22.028
De Graeve, Emiris and Wouters (2009)	-10.291	2.870	17.191	-12.207	3.770	17.977
VAR	-11.626	2.692*	16.900***	-12.630	3.692***	17.901***
BVAR	-12.720*	2.708***	14.520*	-13.592*	3.008*	16.018*
Standard New Keynesian model	-11.533***	3.100	17.714	-	-	-
12 quarters ahead						
	Log determinant statistics	Trace statistics	LPDS	Log determinant statistics	Trace statistics	LPDS
Benchmark DSGE	-7.600**	5.790**	36.880**	-7.790**	7.113***	39.880***
DSGE with no price stickiness	-7.207	5.930	37.293***	-8.017	7.062**	39.751
DSGE with no bond adjustment costs	-6.149	5.811***	38.011	-9.755	7.968	42.159
DSGE with no habits	-7.051	5.961	38.566	-7.990***	7.993	40.502
DSGE with no money target	-5.115	5.952	40.790	-8.502	7.851	45.713
DSGE with no inflation target shock	-7.410***	5.911	40.764	-8.900	7.351	45.799
DSGE with no money velocity shock	-6.595	5.990	40.271	-8.510	8.293	45.250
DSGE with no price markup shock	-7.720	5.890	39.501	-8.140	9.010	47.005
DSGE with no money demand feedback	-7.084	6.074	39.440	-8.194	8.710	45.913
De Graeve, Emiris and Wouters (2009)	-6.291	6.170	39.128	-8.713	7.240	40.174
VAR	-6.626	5.692	37.920	-8.206	8.610	39.012**
BVAR	-8.560*	5.750*	34.010*	-7.370*	6.825*	37.059*
Standard New Keynesian model	-5.703	6.190	38.710	-	-	-

Legend: The three top performing models are indicated by stars, with one star for the best model.