Interest Rates, Money, and Banks in an Estimated Euro Area Model*

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Abstract

This paper estimates a medium scale macroeconomic model with costly banking for euro area data. In addition to data on measures of real activity and prices, we include data on bank loans, loan rates, and reserves for the estimation of the model with Bayesian techniques. We find that loans and holdings of reserves affect banking costs to a small but significant extent. Furthermore, innovations to the demand for reserves are found to contribute more to variations in the policy rate, inflation and output than shocks to the feedback rule for the policy rate, indicating that the demand for central bank money plays a substantial role for macroeconomics dynamics. In contrast, exogenous shifts in banking costs hardly play a role for fluctuations in real activity and prices, while they explain the largest share of variations in reserves.

JEL classification: C54, E52, E32
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1 Introduction

In this paper, we examine the informational content of banking activities and reserves for short-run macroeconomic dynamics in the Euro area. The main purpose of the analysis is to identify if and how banks' demand for high powered money matters for real activity and inflation. Macroeconomic studies on monetary policy have typically supported the view that monetary aggregates are largely irrelevant for output and inflation and can be neglected for the conduct of monetary policy (see e.g. Ireland (2004), or Woodford (2008)). While the majority of these studies have focussed on broader monetary aggregates (such as M1 or M2), we are particularly interested in the role of central bank money. For this, we construct a medium scale macroeconomic model with costly banking, and estimate it using data on bank credit, lending rates, and reserves in addition to macroeconomic time series typically employed for estimation purposes.[2] We find that loans and reserves affect costs of banking to a small but significant extent, while innovations to the demand for reserves are found to substantially contribute to variations in the policy rate, inflation, and output and at a larger magnitude than interest rate rule shocks. Thus, changes in the market for central bank money play a substantial role for the short-run dynamics of macroeconomic aggregates. In contrast, exogenous shifts in banking costs are found to be hardly relevant for fluctuations in macroeconomic variables, except for the variance of reserves, which are to the largest part driven by banking costs shocks.

The model mainly differs from standard medium scale macroeconomic models (like Smets and Wouters (2003) and (2007)) by accounting for banks intermediating funds between households and firms as well as for their holdings of reserves. Banks demand reserves to satisfy a minimum reserve requirement and to reduce costs of loan creation. Banks further hold government bonds, which serve as eligible assets in open market operations. To account for the fact that the European Central Bank (ECB) sets the main refinancing rate, we assume that the central bank controls the price of money in open market operations. Changes in the policy rate might be incompletely passed through by banks to interest rates that are relevant for private agents saving and borrowing decisions. Given that the focus of the paper is a quantitative analysis, we apply a stylized specification of banking costs (see Curdia and Woodford (2011)), which can in principle represent different types of frictions, e.g. incomplete deposit contracts, limited enforcement, or monitoring costs. Hence, we refrain from providing explicit microfoundations for a particular type of imperfection and take an agnostic view by considering a banking cost function with degrees of freedom that are determined by an estimation based on macroeconomic data. By estimating the parameters of the banking

[2] Macroeconomic models developed for estimation purposes either neglect monetary aggregates at all, like Smets and Wouters (2007) and Christiano, Motto, and Rostagno (2014), or consider broader monetary aggregates (that corresponds to M1 or M2), like Christiano, Eichenbaum, and Evans (2005) and Aruoba and Schorfheide (2011). Curdia and Woodford (2011) build a framework with costly banking and central bank money for the analysis of unconventional monetary policy, but do not estimate the model.

cost function, the effects and the size of these costs are identified by fitting the model to data on interest rates, loans, reserves, and other macroeconomic aggregates.

We estimate the model applying Bayesian estimation techniques and Euro area data from 1981Q1 to 2011Q4, thus excluding data since 2012 where reserves have been supplied in an excessive way.[3] As pre-crisis data suggests that banks mainly hold reserves to satisfy a minimum reserve requirement, we compare two versions of the model, where either the elasticities of banking costs with regard to reserves (and loans) are unrestricted (version I) or where we impose that reserves are irrelevant for banking costs (version II). The latter version implies a de facto separability of (central bank) money, which corresponds to the widespread view on the irrelevance of money. For the unrestricted version, we find that loans and reserves significantly affect banking costs, such that reserves are actually non-separable. We further estimate the unrestricted model for a subsample excluding the crisis period (1981Q1 to 2007Q4), to disclose whether the relevance of reserves is mainly induced by the post-crisis sample. The subsample estimate leads to similar results and, in particular, also shows a significant impact of reserves on banking costs.

Overall, the performances of both versions of the model, i.e. the unrestricted version (I) and the restricted version (II), are very similar and are comparable to the results in Smets and Wouters (2003) with regard to the structural relations between non-financial variables and to the transmission of non-financial shocks, while standard deviations and output correlations of both model versions are well in line with the data. The decomposition of individual time series further shows that in both versions productivity shocks contribute to a larger extent to the variation of reserves, loans, and the lending rate than monetary policy shocks, i.e. shocks to a feedback rule for the policy rate. For the unrestricted version (I), we find that innovations to banks' money demand contribute more to fluctuations in most macroeconomic series, including inflation and output, than shocks to the central bank interest rate rule, and that they have particularly been relevant for the variance of the policy rate.[4] A counterfactual analysis further shows that money demand shocks, which shift the banks' valuation of central bank money, specifically allowed to reconcile movements in reserves in the post-2007 period with the prevailing policy rate. Hence, considering the demand for central bank money helps identifying shocks that are relevant for the conduct of monetary policy and for macroeconomics dynamics, and which are typically neglected in macroeconomic studies. In contrast, direct shocks to banking costs are negligible for macroeconomic fluctuations, except for the volatility of reserves.

The remainder is organized as follows. Section 2 presents the model. Section 3 discusses some

[3] In 2012, the ECB introduced some extraordinary monetary operations, which have led to an extreme upward shift in total reserves. These policy measures are not taken into account in the model and are beyond the scope of this paper.

[4] For the restricted version (II), we find that stochastic deviations from the minimum reserve requirement, i.e. money demand shocks, are irrelevant for dynamics of macroeconomic aggregates except for reserves.

equilibrium properties. In Section 4 we describe the calibration and estimation of the model. In Section 5 we present the quantitative results. Section 6 provides a counterfactual analysis and Scetion 7 concludes.

2 The model

Following Smets and Wouters (2003), we model the Euro area as a closed economy. The economy consists of five distinct sectors: The household sector, the production sector, and fiscal policy are close to standard specifications, while the financial intermediation as well as the central bank activities are augmented and modified to allow for the interaction between banks and the central bank. Accounting for ECB practice, we assume that the central bank sets the price of money in open market operations. Banks receive deposits from households and supply loans to firms, while operating under a balance sheet constraint and facing costs associated with bank lending. They further hold reserves and bonds issued by the government, which serve as collateral for reserves in open market operations. Firms rely on external funds for working capital, as in Christiano, Eichenbaum, and Evans (2005), while we assume that households cannot directly lend to firms. Households hold deposits, which provide transaction services, and are assumed to have access to a full set of nominally state contingent claims.[5] The government issues bonds, purchases goods, and raises lump-sum taxes.

2.1 Households

There is a continuum of infinitely lived households indexed with $i \in [0, 1]$. Households have identical preferences and potentially different asset endowments. Household utility increases with consumption and decreases with working time. We further assume that beginning-of-period holdings of deposits $D_{i,t-1}$ at commercial banks provide utility, which serves as a short-cut for modelling transaction services of deposits and thus for considering deposits as a component of broader monetary aggregates. Household i maximizes the expected sum of a discounted stream of instantaneous utilities

$$E_0 \sum_{t=0}^{\infty} \beta^t \xi_t u(c_{i,t}, c_{t-1}, n_{i,t}, D_{i,t-1}/P_t), \tag{1}$$

where E_0 is the expectations operator, $\beta \in (0, 1)$ a discount factor, and ξ_t a time preference shock. Instantaneous utility depends on individual consumption $c_{i,t}$, working time $n_{i,t}$, the real value of bank deposits $d_{i,t} = D_{i,t}/P_t$, where P_t denotes the price of the wholesale good, and c_t aggregate consumption; the latter affecting individual utility via external habits. We apply the following instantaneous utility function: $u_{i,t} = \frac{1}{1-\sigma}(c_{i,t} - hc_{t-1})^{1-\sigma} + \varrho \frac{1}{1-\varphi}\left(d_{i,t-1}\pi_t^{-1}\right)^{1-\varphi} - \nu_t \frac{1}{1+\upsilon} n_{i,t}^{1+\upsilon}$, such that $u_{i,ct} = (c_{i,t} - hc_{t-1})^{-\sigma}$, $u_{i,dt} = \varrho \pi_t^{-1}(d_{i,t-1}/\pi_t)^{-\varphi}$ and $u_{i,nt} = -\nu_t n_{i,t}^{\upsilon}$, where $\sigma > 0$, $\varphi > 0$, $\upsilon \geq 0$, and $\varrho \geq 0$, $\pi_t = P_t/P_{t-1}$ denotes the inflation rate, and ν_t a labor supply shock.

[5] Market completeness is assumed to facilitate aggregation and comparisons to related studies.

Household i supplies differentiated labor services at the nominal wage rate $W_{i,t}$, invests in deposits, and trades state contingent claims $S_{i,t}$:

$$(D_{i,t}/R_t^d) - D_{i,t-1} + E_t[\varphi_{t,t+1}S_{i,t+1}] - S_{i,t} + P_t c_{i,t} \leq W_{i,t}n_{i,t} + P_t pr_{i,t} + P_t\tau_{i,t}, \tag{2}$$

where R_t^d denotes the rate of return on deposits, $\varphi_{t,t+1}$ a stochastic discount factor, $\tau_{i,t}$ a lump-sum tax, and $pr_{i,t}$ collects profits from firms, retailers, and banks. Household $i's$ borrowing is restricted by $D_{i,t} \geq 0$ and $\lim_{s\to\infty} E_t\varphi_{t,t+s}S_{i,t+s+1} \geq 0$. Maximizing the objective (1) subject to (2) and the borrowing constraints, for given initial values $D_{i,-1} > 0$, $S_{i,0}$, $c_{-1} > 0$ leads to first order conditions for consumption, deposits, and contingent claims, which can be summarized as $\xi_t u_{c,i,t} = \lambda_{i,t}$,

$$1/R_t^d = \beta E_t\left[\frac{1}{\pi_{t+1}}\frac{\xi_{t+1}u_{c,i,t+1}}{\xi_t u_{c,i,t}}\left(1+\frac{u_{d,i,t+1}}{u_{c,i,t+1}}\right)\right], \tag{3}$$

$$\varphi_{t,t+1} = \beta\frac{1}{\pi_{t+1}}\frac{\xi_{t+1}u_{c,i,t+1}}{\xi_t u_{c,i,t}}, \text{ where } R_t = 1/E_t\varphi_{t,t+1}, \tag{4}$$

and (2) holding with equality as well as the transversality conditions. A comparison of (3) and (4) shows that the deposit rate R_t^d tends to be smaller than the risk-free rate R_t, as deposits increase utility. Combining (3) and (4) leads to a version of deposit demand, $1 = E_t[R_t^d\varphi_{t,t+1}(1 + u_{d,i,t+1}/u_{c,i,t+1})]$, which accords to a conventional demand condition for an assets that provide transaction services (except for the deposit rate R_t^d). It implies that the demand for real deposits tends to decrease with the spread between the risk-free rate and the deposit rate. In contrast to the common approach of specifying monetary policy in macroeconomic models (see e.g. Smets and Wouters (2007)), we do not assume that the central bank is able to control the risk-free rate directly. Instead, we account for the fact that the European central bank sets the price of money in open market operations (i.e. the main refinancing rate), while other interest rates (including R_t^d and R_t) are endogenously determined.[6]

We assume that households monopolistically supply differentiated labor services $n_{i,t}$, which are transformed into aggregate working time n_t as $n_t^{1-1/\varepsilon_n} = \int_0^1 n_{i,t}^{1-1/\varepsilon_n} di$, where $\varepsilon_n > 1$ is the elasticity of substitution between differentiated labor services. Cost minimization then leads to the following labor demand

$$n_{i,t} = (W_{i,t}/W_t)^{-\varepsilon_n} n_t, \tag{5}$$

where $W_t^{1-\varepsilon_n} = \int_0^1 W_{i,t}^{1-\varepsilon_n} di$ and W_t denotes the aggregate wage rate. We assume that nominal wages $W_{i,t}$ are set in staggered way, as in Erceg et al. (2000). In any period, only a constant fraction $1-\varsigma$ (where $\varsigma \in (0,1)$) of households receives a random signal allowing household i to re-optimize its nominal wage. The remaining fraction adjusts the nominal wage rate mechanically

[6]Further note that time preference shocks ξ_t, which differ from ad-hoc risk premium shocks that are introduced by Smets and Wouters (2007) to account for differences between the marginal rate of intertemporal substitution and the monetary policy rate, apply to all intertemporal decisions and prices (see also Sections 2.2 and 2.3).

with the past inflation rate π_{t-1} , such that $W_{i,t} = \pi_{t-1} W_{i,t-1}$ in this case. If household i is allowed to change its wage rate in period t, it maximizes (1) subject to labor demand (5), leading to the following first order condition for the wage rate $\widetilde{W}_t$

$$E_t \sum_{s=0}^{\infty} \beta^s \varsigma^s \left[\frac{\xi_{t+s} u_{c,i,t+s}}{\xi_t u_{c,i,t}} n_{i,t+s} \left(\frac{\left(\Pi_{k=1}^s \pi_{t+k-1}\right) \widetilde{W}_t}{P_{t+s}} - \frac{\varepsilon_n}{\varepsilon_n - 1} mrs_{i,t+s} \right) \right] = 0, \tag{6}$$

where $mrs_{i,t}$ denotes the household i's marginal rate of substitution between consumption and leisure, $mrs_{i,t} = -u_{i,nt}/u_{c,i,t}$. Using $\left(\Pi_{k=1}^s \pi_{t+k-1}\right) \widetilde{W}_t / P_{t+s} = (\pi_t / \pi_{t+s}) \widetilde{w}_t$ where $\widetilde{w}_t = \widetilde{W}_t / P_t$, (6) can be written as $f_t^1 = f_t^2$, where $f_t^1 = \widetilde{w}_t \xi_t u_{c,i,t} \left(w_t / \widetilde{w}_t \right)^{\varepsilon_n} n_{i,t} + E_t \beta \varsigma [(\pi_{t+1}/\pi_t) \left(\widetilde{w}_{t+1} / \widetilde{w}_t \right)]^{\varepsilon_n - 1} f_{t+1}^1$ and $f_t^2 = \epsilon_{w,t} \nu \mu_w \xi_t \left(w_t / \widetilde{w}_t \right)^{(1+v)\varepsilon_n} n_{i,t}^{(1+v)} + \beta \varsigma [(\pi_{t+1}/\pi_t) \left(\widetilde{w}_{t+1} / \widetilde{w}_t \right)]^{(1+v)\varepsilon_n} f_{t+1}^2$, where $\mu_w = \varepsilon_n / (\varepsilon_n - 1)$ and we defined $\epsilon_{w,t} = v_t / v$ with v as the mean of v_t. Hence, $\epsilon_{w,t}$ is a shock that is equivalent to a wage-markup shock (see Chari, Kehoe, and McGrattan (2009) for a critical discussion on this issue). As trade in contingent assets implies that (the growth rate of) the marginal utility of consumption is the same across households (see 4), any household who is permitted to optimize chooses the same nominal wage rate $\widetilde{W}_t$. The aggregate real wage rate $w_t = W_t / P_t$ then evolves according to $w_t = [\varsigma w_{t-1}^{1-\varepsilon_n} \left(\pi_t / \pi_{t-1} \right)^{\varepsilon_n - 1} + (1 - \varsigma) \widetilde{w}_t^{1-\eta}]^{1/(1-\varepsilon_n)}$.

2.2 Production

The production sector consists of monopolistically competitive intermediate goods producing firms, monopolistically competitive retailers, and perfectly competitive bundlers who supply the final wholesale good.

There is a continuum of monopolistically competitive intermediate goods producing firms. Firm $j \in [0, 1]$ produces intermediate goods $y_{j,t}^m$ with labor, which is hired from households, and with their own stock of capital $k_{j,t}$. Individual intermediate goods $y_{j,t}^m$ are sold at the price $Z_{j,t}$ to retailer k, which demand individual intermediate goods according to $y_{j,t}^m = \left(Z_{j,t} / Z_t \right)^{-\varepsilon_{m,t}} y_{k,t}$, where $\varepsilon_{m,t}$ denotes a random substitution elasticity that serves as a cost-push shock. The production technology is identical for all firms j and exhibits standard neoclassical properties: $y_{j,t}^m = a_t n_{j,t}^{\alpha} k_{j,t-1}^{1-\alpha}$, where $\alpha \in (0, 1)$ and a_t is a random productivity level with mean one. A firm j accumulates physical capital $k_{j,t}$ by investing $x_{j,t}$ and subject to adjustment costs $\Gamma_{X,t} = \Gamma_X \left(x_{j,t} / x_{j,t-1} \right)$ associated with changes in investment

$$k_{j,t} - (1 - \delta) k_{j,t-1} = \epsilon_{x,t} \left(1 - \Gamma_{X,t} \right) x_{j,t}, \tag{7}$$

where $\Gamma_{X,t} = \frac{\gamma_X}{2} \left(\frac{x_{j,t}}{x_{j,t-1}} - 1 \right)^2$ with $\gamma_X > 0$ and $\delta \in (0, 1)$ denotes the depreciation rate and $\epsilon_{x,t}$ an investment-specific technology shock. Firms have access external funds via one-period risk free bank loans $L_{j,t}$ at the current price $1/R_t^L$. For simplicity, we assume that firm owners receive claims v_t^f on current period profits (including repayment of previous period debt) at the beginning of each period, such that v_t^f is given by

$$P_t v_t^f = Z_{j,t} a_t n_t^{\alpha} k_{j,t-1}^{1-\alpha} - P_t w_t n_{j,t} + \left(L_{j,t}/R_t^L\right) - P_t x_{j,t} - L_{j,t-1}, \tag{8}$$

where $Z_{j,t}$ denotes the price of the intermediate good. Demand for external funds is then induced by assuming that wages have to be paid on workers' banking accounts before goods are sold. Firm $j's$ current period demand for one-period loans $L_{j,t}$ from banks thus satisfies:

$$L_{j,t}/R_t^L \geq w_t n_{j,t}. \tag{9}$$

We assume that, in equilibrium, firms fully repay one unit of currency per unit of loan in the subsequent period, such that R_t^L denotes a risk-free rate of return on loans. We assume that firm j maximizes the present value of dividends, $\max E_t \sum_{k=0}^{\infty} \phi_{t,t+k} v_{t+k}^f$, s.t. $y_{j,t}^m = (Z_{j,t}/Z_t)^{-\varepsilon_{m,t}} y_{k,t}$, (7)-(9), and a no-Ponzi game condition, where $\phi_{t,t+k} = \varphi_{t,t+1}\pi_{t+1} \cdot \varphi_{t+1,t+2}\pi_{t+2} \cdot \ldots \cdot \varphi_{t+k-1,t+k}\pi_{t+k}$ denotes the firms' stochastic discount factor (see 2), given $k_{j,-1} > 0$ and $x_{j,-1} > 0$. The first order conditions for labor and loans are

$$\left(mc_{j,t}/\mu_{p,t}\right) \alpha a_t n_{j,t}^{\alpha-1} k_{j,t-1}^{1-\alpha} = w_t R_t^L / R_t, \tag{10}$$

$$l_{j,t}/R_t^L = w_t n_{j,t}, \text{ if } R_t^L > R_t \text{ or } l_{j,t}/R_t^L \geq w_t n_{j,t}, \text{ if } R_t^L = R_t, \tag{11}$$

where we defined $mc_{j,t} = Z_{j,t}/P_t$ and $\mu_{p,t} = \frac{\varepsilon_{m,t}}{\varepsilon_{m,t}-1}$. Labor demand (10) is effectively altered by the working capital constraint (9), if the lending rate R_t^L exceeds the risk-free rate R_t, which will be the case in equilibrium (mainly) due to positive banking costs that banks pass to the lending rate. The working capital constraint (11) will thus be binding throughout the analysis. The first order conditions for investment expenditures and physical capital are further given by

$$1 = q_{j,t}\epsilon_{xt} \left(1 - \Gamma_{X,t} - \Gamma'_{X,t} \frac{x_{j,t}}{x_{j,t-1}}\right) + E_t \left[\phi_{t,t+1} q_{j,t+1} \epsilon_{x,t+1} \Gamma'_{X,t+1} \left(\frac{x_{j,t+1}}{x_{j,t}}\right)^2\right], \tag{12}$$

$$q_{j,t} = E_t[\phi_{t,t+1} q_{j,t+1}(1-\delta)] + E_t[\phi_{t,t+1} \left(mc_{j,t+1}/\mu_{p,t+1}\right)(1-\alpha) n_{j,t+1}^{\alpha} k_{j,t}^{-\alpha}], \tag{13}$$

where q_t denotes the standard Tobin's q. Given that all intermediate goods producing firms behave in an identical way, aggregate supply simply equals $y_t^m = y_{j,t}^m$.

A monopolistically competitive *retailer* $k \in [0,1]$ buys intermediate goods $y_{j,t}^m$ at the price $Z_{j,t}$, combines them to the retail good $y_{k,t}$ according to $(y_{k,t})^{\frac{\varepsilon_{m,t}-1}{\varepsilon_{m,t}}} = \int_0^1 \left(y_{j,t}^m\right)^{\frac{\varepsilon_{m,t}-1}{\varepsilon_{m,t}}} dj$, and sells it at the price $P_{k,t}$ to perfectly competitive *bundlers*. The latter bundle the goods $y_{k,t}$ to the final consumption good y_t with the technology, $y_t^{\frac{\varepsilon-1}{\varepsilon}} = \int_0^1 y_{k,t}^{\frac{\varepsilon-1}{\varepsilon}} dk$, where $\varepsilon > 1$ is the elasticity of substitution and the cost minimizing demand for $y_{k,t}$ is $y_{k,t} = (P_{k,t}/P_t)^{-\varepsilon} y_t$. A fraction $1-\phi$ of the retailers set their price in an optimizing way. The remaining fraction $\phi \in (0,1)$ of retailers adjust the price according to partial indexation to the previous period inflation rate π_{t-1}, $P_{k,t} =$

$\pi_{t-1}^{\iota} P_{k,t-1}$. The problem of a price adjusting retailer is

$$\max_{\widetilde{P}_{k,t}} E_t \sum_{s=0}^{\infty} \phi^s \beta^s \phi_{t,t+s} \left(\frac{\left(\Pi_{k=1}^{s} \pi_{t+k-1}^{\iota}\right) \widetilde{P}_{k,t}}{P_{t+s}} - mc_{t+s} \right) y_{k,t+s}, \tag{14}$$

where $mc_t = Z_t/P_t$ and $Z_t^{1-\varepsilon_{m,t}} = \int_0^1 Z_{j,t}^{1-\varepsilon_{m,t}} dj$. The first order condition (14) can equivalently be written as $\tilde{Z}_t = \frac{\varepsilon}{\varepsilon-1} Z_t^1/Z_t^2$, where $\tilde{Z}_t = \widetilde{P}_t/P_t$, $Z_t^1 = \xi_t c_t^{-\sigma} y_t mc_t + \phi\beta E_t \left(\pi_{t+1}/\pi_t^{\iota}\right)^{\varepsilon} Z_{t+1}^1$ and $Z_t^2 = \xi_t c_t^{-\sigma} y_t + \phi\beta E_t \left(\pi_{t+1}/\pi_t^{\iota}\right)^{\varepsilon-1} Z_{t+1}^2$. With perfectly competitive bundlers and the homogenous bundling technology, the price index P_t for the final consumption good satisfies $P_t^{1-\varepsilon} = \int_0^1 P_{k,t}^{1-\varepsilon} dk$. Hence, we obtain $1 = (1-\phi)\, \tilde{Z}_t^{1-\varepsilon} + \phi \left(\pi_t/\pi_{t-1}^{\iota}\right)^{\varepsilon-1}$, where $\iota \in [0,1]$ measures the degree of indexation. In a symmetric equilibrium, $y_{j,t}^m = y_{k,t}$ will hold and thus $y_t = a_t n_t^{\alpha} k_{t-1}^{1-\alpha}/s_t$, where $s_t = \int_0^1 \left(P_{k,t}/P_t\right)^{-\varepsilon} dk$ and $s_t = (1-\phi)\tilde{Z}_t^{-\varepsilon} + \phi s_{t-1} \left(\pi_t/\pi_{t-1}^{\iota}\right)^{\varepsilon}$ given s_{-1}.

2.3 Banks

The basic role of banks in this model is to intermediate funds between households, firms, and the public sector. There is a continuum of perfectly competitive financial intermediaries, i.e. commercial banks. We account for the fact that in each period banks have to satisfy a balance sheet constraint and a minimum reserve requirement, which can be justified by (unmodelled) early withdrawels of deposits. We further consider real resource costs stemming from the origination and the supply of loans to firms. Following Curdia and Woodford (2011), these banking costs are increasing in the amount of loans and decreasing in the amount of reserves that are available for the liquidity management of credit supply. Banks receive deposits from household $D_t = \int D_{i,t} di$, supply loans $L_t = \int L_{j,t} dj$, and further hold reserves M_t and multiperiod government bonds B_t, which are traded at a price q_t^B in period t and deliver a payoff p_{t+1}^B in period $t+1$ (see Section 2.4). The bank balance sheet constraint requires that banks accept deposits to the amount that equals the expected payoffs from assets (see Curdia and Woodford (2011)):

$$D_t = M_t + E_t p_{t+1}^B B_t + L_t. \tag{15}$$

Banks exchange eligible assets against reserves with the central bank in open market operations, i.e. they use government bonds as collateral to get additional reserves $I_t = M_t - M_{t-1}$ from the central bank. We assume (without modeling) that eligible assets are abundantly available by banks, i.e. that $I_t \leq B_t/R_t^m$ is not binding, where $R_t^m > 1$ denotes the main refinancing rate that serves as the policy instrument. To satisfy a minimum reserve requirement, banks have to hold reserves as a minimum a fraction of their deposits:

$$M_t \geq \mu_t D_t. \tag{16}$$

where we allow for time-variations in the minimum reserve ratio (see below). We specify costs of banking activities in a stylized way. While lacking an explicit microfoundation, we introduce a functional form of real resource costs that can be identified by estimating few parameters.[7] We assume that banks face real resource costs when they fund and originate loans to firms. Following Curdia and Woodford (2011), we assume that these costs Ξ_t are increasing in the amount of loans, $\Xi_{l,t} \geq 0$, and decreasing in the amount of reserves held by banks, $\Xi_{m,t} \leq 0$. In particular, we assume that excess reserves. i.e. total reserves $M_{t-1} + I_t$ net of required reserves, reduce banks' costs:

$$\Xi_t = \Xi(L_t/P_t, (M_{t-1} + I_t - \mu_t D_{t-1})/P_t), \tag{17}$$

For the banking costs Ξ_t, we apply the specific form: $\Xi_t = \zeta_t \left([L_t/P_t]/[(M_{t-1} + I_t - \mu_t D_{t-1})/P_t]^{\omega}\right)^{\eta_{rc}}$, where $\omega \geq 0$, $\eta_{rc} \geq 0$, and the stochastic term ζ_t serves as a shock to banking costs. Thus, ω is the ratio between the elasticity of banking costs with regard to excess reserves $\omega\eta_{rc}$ and the elasticity of banking costs with regard to loans is η_{rc}. Note that $\omega = 0$ will imply that no excess reserves are held. Given that eligible assets are discounted at the rate R_t^m in open market operations, acquisition of reserves I_t is associated with costs $I_t(R_t^m - 1)$. Real profits of a bank v_t^I are thus given by

$$P_t v_t^I = (D_t/R_t^d) - D_{t-1} - q_t^B B_t + p_t^B B_{t-1} - (L_t/R_t^L) + L_{t-1} - M_t + M_{t-1} - I_t(R_t^m - 1) - P_t \Xi_t, \tag{18}$$

where q_t^B (p_t^B) denotes the end(beginning)-of-period price of government bonds. Banks maximize the sum of discounted profits, where they take the balance sheet constraint (15) as well as the minimum reserve requirement (16) into account: $\max E_t \sum_{k=0}^{\infty} \phi_{t,t+k} v_{t+k}^I$, s.t. (15)-(18), and a no-Ponzi game condition $\lim_{s\to\infty} E_t \phi_{t,t+s} D_{i,t+s} \geq 0$ as well as $L_t \geq 0$, $B_t \geq 0$, and $M_t \geq 0$. The first order conditions with regard to deposits, bonds, loans, money holdings, and reserves hold, which can be combined to

$$1/R_t^d = 1 - E_t\left(R_{t+1}^m - 1\right)\left(1 - \mu_{t+1}\right)\varphi_{t,t+1}, \tag{19}$$

$$1/E_t R_{t+1}^b = 1/R_t^d - E_t\left(R_{t+1}^m - 1\right)\mu_{t+1}\varphi_{t,t+1}, \tag{20}$$

$$1/R_t^L = 1/R_t^d - E_t\left(R_{t+1}^m - 1\right)\varphi_{t,t+1}\mu_{t+1} - \Xi_{l,t}, \tag{21}$$

$$\Xi_{m,t} = 1 - R_t^m + \eta_t, \tag{22}$$

(where $\varphi_{t,t+1} = \phi_{t,t+1}\pi_{t+1}^{-1}$) as well as (15), and the complementary slackness conditions

$$\eta_t\left(m_t - \mu_t d_{t-1}\pi_t^{-1}\right) = 0,\ \eta_t \geq 0,\ m_t - \mu_t d_{t-1}\pi_t^{-1} \geq 0, \tag{23}$$

[7] Alternative approaches to specify financial intermediation and associated imperfecions in a more explicit way, like Gertler and Karadi (2011), are theoretically more appealing, but are less suited for the quantitative analysis of banks' reserve demand.

where $m_t = M_t/P_t$, $d_t = D_t/P_t$, and η_t denotes the multiplier on the minimum reserve requirement (16) and R^b_t is defined as the one-period rate of return on state contingent government bonds, $R^b_t = p^B_t/q^B_{t-1}$. Condition (19) relates the rate of return on deposits to the expected policy rate R^m_t, taking into account the costs induced by required reserves. The return on risk-free government bonds (see 20) relates to the return on deposits and to the marginal costs of holding deposits. The return on loans additionally accounts for the marginal effects of loans on the banking costs (see 21). Finally, banks' demand for reserves satisfies (22), which relates the payoff from holding reserves (via reductions of the banking costs) to the policy rate, i.e. the costs of acquiring reserves in open market operations, and to the multiplier on the minimum reserve requirement. The constraints (15), (16), and the optimality conditions (19)-(22), describe the banks' behavior.

We will consider two scenarios that differ with regard to the elasticity $\omega\eta_{rc}$ of the banking costs with respect to excess reserves. When the elasticity equals zero, $\omega = 0 \Rightarrow \Xi_{m,t} = 0$, banks will only hold required reserves, as (22) implies $\eta_t > 0$ for $R^m_t > 1$ and thus money demand is given by $m_t = \mu_t d_{t-1}\pi_t^{-1}$ (see 23). If, however, the elasticity ω is positive, banks will hold more reserves than required (see 17), such that the minimum reserve requirement (16) is slack and money demand is characterized by (22). For both money demand specifications, we include a disturbance term $\epsilon_{m,t}$, which in the latter case enters (22) instead of the multiplier η_t. If $\omega = 0$, the disturbance term leads to exogenous shifts in the reserve requirement ratio $\mu_t = \mu\epsilon_{m,t}$ (see 16), such that money demand is given by

$$\begin{aligned} &\Xi_{m,t} = 1 - R^m_t + \epsilon_{m,t}, \text{ if } \ \omega > 0 \text{ (version } I) \\ &m_t = \mu\epsilon_{m,t} d_{t-1}\pi_t^{-1}, \quad \text{ if } \ \omega = 0 \text{ (version } II) \end{aligned} \tag{24}$$

The version of the model where reserves affect banking costs, $\omega > 0$, will be labelled version I. For $\omega = 0$, the version will be labelled version II. Throughout the remainder of the analysis, we will refer to shocks $\epsilon_{m,t}$ as money demand shocks. Further note that the mean reserve requirement ratio μ will be held constant at 2% consistent with the data.

2.4 The government

The government raises lump-sum taxes τ_t and purchases goods g_t. To allow for state contingency of public debt, we assume that the government issues nominal debt as perpetuities with coupons payments that decay exponentially at the rate $\rho \in [0, 1]$, which exhibit a (real) state-contingent beginning-of-period price p^B_t. Since bonds issued in period $t - s$ are equivalent to ρ^s bonds issued in t, we assume – without loss of generality – that all long-term debt are of one type (which implies that the government redeems all old bonds in each period). The price of a perpetuity issued in period t is q^B_t, while it pays out $1+\rho q^B_{t+1}$ units of currency in period $t+1$, such that $p^B_t = 1+\rho q^B_t$. Let B^T_t denote the total stock of newly issued bonds, which is either held by banks or the central bank: $B_t^T = B_t + B_t^c$. The flow budget constraint of the government can be written as

$$q_t^B B_t^T + P_t sp_t = \left(1 + \rho q_t^B\right) B_{t-1}^T, \quad \text{with } p_0^B B_{-1}^T > 0, \tag{25}$$

or in real terms $q_t^B b_t^T + sp_t = \left(1 + \rho q_t^B\right) b_{t-1}^T \pi_t^{-1}$, where $b_t^T = B_t^T / P_t$ and sp_t denotes real surpluses $sp_t = \tau_t + \tau_t^m - g_t$, given $b_{-1}^T \geq 0$, and τ_t^m denotes central bank transfers. The government is perfectly committed to pay the coupon ρ and raises the primary surplus with the current market value of outstanding debt. For simplicity, we define $\widetilde{\tau}_t$ as total revenues from taxation and from central bank transfers, $\widetilde{\tau}_t = \tau_t + \tau_t^m$, and assume that the government controls $\widetilde{\tau}_t$ according to the following feedback rule in terms of deviations from steady state values (which are denoted without time indices):

$$\widetilde{\tau}_t - \widetilde{\tau} = g_t - g + \rho_{\tau b}\left(p_t^B b_{t-1}^T \pi_t^{-1} - \overline{pb}^T \pi^{-1}\right) + \rho_{\tau y}\left(y_t - y\right), \tag{26}$$

where $\rho_{\tau b} > 0$ and $\rho_{\tau y} \geq 0$. We assume that the government targets a long-run real value for public debt $\overline{pb}^T$ that has to equal its long-run equilibrium value $\overline{pb}^T = p^B b^T$. We further restrict our attention to sufficiently large values for $\rho_{\tau b}$ to ensure that intertemporal solvency is satisfied in all states and periods. To complete the specification of fiscal policy, we assume that the sequence of government spending $\{g_t\}_{t=0}^{\infty}$ is stochastic and evolves according to $g_t = \rho_g g_{t-1} + (1-\rho_g)g + \varepsilon_{g,t}$, where $g > 0$, $\rho_g \in (0,1)$, and $\varepsilon_{g,t}$ is i.i.d. with mean zero. Hence, lump-sum transfers are set by the government to satisfy (26) for given expenditures and central bank transfers.

2.5 The central bank

The central bank supplies money in open market operations $M_t = \int_0^1 M_{i,t} di$, such that newly issued money satisfies $I_t = M_t - M_{t-1}$, for which the central bank receives government bonds B_t^c. Hence, in open market operations t the central bank receives $I_t R_t^m$ units of bonds against I_t units of money, such that its budget constraint reads

$$q_t B_t^c - p_t^B B_{t-1}^c + P_t \tau_t^m = \left(M_t - M_{t-1}\right) R_t^m. \tag{27}$$

where B_t^c denotes the stock of government bonds held by the central bank. In accordance with central bank practice in the Euro area, the central bank transfers its interest earnings from issuing money via repos and from holding interest bearing assets: $P_t \tau_t^m = E_t p_{t+1}^B B_t^c - q_t B_t^c + (R_t^m - 1)(M_t - M_{t-1})$. In principle, transfers can be negative when a fall in bond prices exceeds the interest earnings from money supply.[8] Substituting out transfers in (27), central bank bond holdings evolve according to $E_t p_{t+1}^B B_t^c - p_t^B B_{t-1}^c = M_t - M_{t-1}$, and, by assuming that initial stocks satisfy $p_0^B B_{-1}^c = M_{-1}$,

$$E_t p_{t+1}^B B_t^c = M_t, \tag{28}$$

[8] See (Hall and Reis, 2012) for a comprehensive discussion of central bank solvency.

which corresponds to the banks' balance sheet constraint (15). For the policy rate R_t^m, which in the Euro area accords to the main refinancing rate, we apply a conventional specification and consider a simple feedback rule, which describes how the central bank adjusts the policy rate in response to changes in its own lags, in inflation, and the output-gap as a measure for real activity:

$$R_t^m = \left(R_{t-1}^m\right)^{\rho_R} (R^m)^{1-\rho_R} (\pi_t/\pi)^{\rho_\pi(1-\rho_R)} (y_t/y)^{\rho_y(1-\rho_R)} \exp \varepsilon_{r,t}, \tag{29}$$

where $R^m > 1$, $\rho_R \geq 0$, $\rho_\pi \geq 0$, and $\rho_y \geq 0$, and the $\varepsilon_{r,t}' s$ are normally and i.i.d. with $E_{t-1}\varepsilon_{r,t} = 0$. As common in the literature, we assume that the central bank chooses the inflation target $\overline{\pi}$, which has to be equal to the long-run equilibrium inflation rate π, for which the central bank sets its instruments in a consistent way.

3 Equilibrium

In this Section, we describe some main equilibrium properties of the model. In equilibrium, all markets clear and households as well as intermediate goods producing firms behave in an identical way (see Appendix A.1 for a full set of equilibrium conditions). Throughout the analysis, we will restrict our attention to equilibria where the working capital constraint of firms (9) is binding, which requires $R_t^L > R_t$. We then consider two versions (I and II,see 24), which differ with regard to money elasticity of banking costs and the multiplier on the minimum reserve requirement (16), which is binding ($\eta_t > 0$) in version II and slack ($\eta_t = 0$) in version I. The definitions of rational expectations equilibria for both versions are given in Appendix A.1.

(Non)-separability of central bank money When the elasticity of banking costs with respect to money demand $\omega\eta_{rc}$ is zero (version II), which we will impose in the estimations by $\omega = 0$, banks' holdings of reserves simply satisfy $m_t = \mu\epsilon_{m,t}d_{t-1}\pi_t^{-1}$ for $R_t^m > 1$ (see 24), while they are otherwise irrelevant for the decision of banks. Hence, reserves can separately be examined from the equilibrium real allocation and the associated price system.[9] If, however, the elasticity ω is strictly positive (version I), reserves are not separable from the equilibrium real allocation and the associated price system. To give a preview, when we estimate the unrestricted version of the model, we find that the elasticity $\omega\eta_{rc}$ is small but strictly positive confirming that reserves are indeed non-separable. The (non-)separability of reserves in the long-run equilibrium is analyzed in Appendix A.2.

Monetary transmission Models with frictionless financial markets (e.g. Smets and Wouters (2003)) are typically characterized by a single nominal interest rate and the assumption that the central bank controls the risk-free nominal interest rate R_t, which – in real terms – governs the

[9] It should be noted that shocks to the minimum reserve requirement are in general non-neutral, as they affect the banking decision via the balance sheet (15).

marginal rate of intertemporal substitution, $\beta E_t[\xi_{t+1} u_{c,t+1}/(\xi_t u_{c,t})]$. In our model, the central bank is – in accordance with the ECB practice – assumed to control the price of money in open market operations, which – via profit maximizing behavior of competitive banks – affects the interest rates on government bonds, deposits, and loans, where the latter two rates can be affected by financial frictions. Specifically, the pass-through of policy rate changes to these interest rates is affected by the balance sheet constraint (15) and banking costs (17).

To see how policy rate changes are transmitted, assume that the fraction μ of deposits which lowers the cost reducing effect of reserves equals zero (μ will actually take a value close to zero). Then, the first order condition for bank deposits (19) and the bank's demand for additional reserves (22) can be combined to

$$1/R_t^d = 1 - E_t\varphi_{t,t+1}\left(R_{t+1}^m - 1\right), \tag{30}$$

where the discount factor accounts for the property that the opportunity costs of reserves held by banks in a particular period relate to the current deposit rate R_t^d, whereas their benefit from saving costs of money acquisition becomes effective in the subsequent period. For the particular case where deposits do not provide transaction services, $u_{d,t} = 0$, the households' optimality conditions (3) and (4) reveal that deposits are equivalent to a portfolio of claims with a risk-free payoff, such that $R_t^d = 1/E_t\varphi_{t,t+1}$. For this case, (30) implies that the rate of return on households' saving devices closely relates the expected future policy rate, since $E_t\varphi_{t,t+1}R_{t+1}^m = 1$ and $R_t^d \simeq E_t R_{t+1}^m$. Thus, for this simplified version ($\mu = u_{d,t} = 0$), changes in the monetary policy rate are (almost) completely passed through to the rate that governs the households' consumption and savings decision as in standard models.

For the more general case $u_{d,t} \geq 0$, (30) implies up to a first-order approximation at a steady state $[R - (R_m - 1)] \cdot \widehat{R}_t^d = R^m \cdot E_t \widehat{R}_{t+1}^m - \{R^m - 1\} \cdot \widehat{R}_t$ (where variables with a hat denote percentage deviations from the particular steady state value), which shows that changes in the deposits rate are mainly induced by changes in the expected policy rate (given that the coefficient in the curly brackets is relatively small). Put differently, the net deposit rate $i^d = R^d - 1$ approximately equals the net policy rate $i^d = i^m/(1 + R - R^m) \approx i^m$ in a steady state where the policy rate is close to the risk-free rate R, while it will be slightly smaller for plausible values of μ. This effect also tends to reduce the deposit rate compared to the bond rate and the lending rate (see 20 and 21), while the latter additionally differs from the deposit rate by marginal costs of loans. Further note that the real deposit rate can deviate from the risk-free rate due to the marginal utility of deposits that is considered as a short-cut for their transactions services (see 3).

4 Parameter Estimates

The model is estimated with Bayesian techniques using Euro area data from 1981Q1 to 2011Q4. Precisely, we estimate three versions of the model: a version where we do not restrict the parameter of the banking cost function (version I), a version where the elasticity of banking costs with respect to reserves is restricted to be zero, $\omega = 0$ (version II), and an unrestricted version which is estimated for the subsample 1981Q1 to 2007Q4 (version III). The latter is estimated to disclose whether the parameter estimates are particularly affected by developments of the recent financial crisis. In this Section, we describe the data and the estimation of parameters. Before, we summarize how we set those that are fixed in the estimation procedure.

4.1 Restricted parameters and priors

Table 1 summarizes the values of the parameters that are not estimated in this paper. Most parameters in the model are shared with comparable studies, while several other parameters are less common or even specific to the model and are chosen to match observable steady state relations and averages for our sample period .

Starting with the common parameters, we use a value of 2 for the intertemporal elasticity of substitution for working time and for deposits, and a degree of habit formation of 0.55.[10] Households devote one third of their time on working, which implies $\nu = 142.83$, and the household discount factor is set to 0.9901. The capital depreciation rate is set at 0.03, the labor share at 0.7 and investment adjustment costs are set equal to 6.00 (compare Smets and Wouters (2003) for a further discussion on the parameters for Euro area). The substitution elasticities ε and ε_n are set to 6, implying steady state mark-ups of 1.2. The steady state inflation is set to 2 percent to match average inflation in the latter part of the sample and to be broadly in line with the ECB's definition of price stability. The average annual nominal monetary policy interest rate is set to 6 percent per annum. The government spending share is set to 0.18.

Regarding the less common parameter, we set the duration of the long-term console equal to 10 years, implying a decay factor ρ of 0.986. The long-run debt-to-GDP ratio is further set at 70 percent, approximating the values in the Euro area prior to the financial crisis. The utility weight of holding deposits φ^d is set at 0.04, which is consistent with a long-run equilibrium ratio of deposit-to-gdp of 1.2.[11]. We further set the share of reserves μ that are held for the liquidity

[10] In the setting of the model with a consumption preference shock and habit formation it is not possible to identify the persistence of the preference shock and the habit parameter separately. To avoid the identification problem the habit formation parameter is calibrated to 0.55, compare Smets and Wouters (2003) for the value of the habit formation parameter. The problem of the weakly identified preference shock/habit formation is discussed in Chari, Kehoe, and McGrattan (2007).

[11] In the model the deposits are narrowly defined as the bank deposits of households, which are then calibrated in line with the Worldbank's estimate of 'bank deposits to GDP'. Note that the ratio of 'bank deposits to GDP ' has been increasing over the sample for the euro area, where we use the value of the ratio towards the end of the sample.

Table 1: Values assigned to the calibrated parameters

Parameter	Value	Description
υ	2	Frisch labor supply elasticity
φ^d	2	Intertemporal substitution elasticity of deposits
β	0.9901	Discount factor
ϱ	0.04	Deposit weight in the utility function
n	1/3	time devoted to work
h	0.55	Habit formation parameter
δ	0.03	Depreciation rate
α	0.7	Labor share
ε	6.00	Substitution elasticity for intermed. goods
ε_n	6.00	Substitution elasticity for working time
μ	0.02	Minimum reserve ratio
λ	0.1	Fraction of money held outright
ρ	0.986	Decay factor of government bond

Note: This table shows the values for the calibrated parameters. In addition to these parameters we have used the following steady state ratios: an annual inflation target ($\bar{\pi}$) of 2%, a value of 4 percent for long term real rate, a ratio of the government spending to GDP of 18, a debt to GDP ratio of 0.7 and a deposit to GDP ratio of 1.2.

management of deposits equal to 0.02 and the share of money supplied via outright purchases to repurchase agreements equal to 0.1, which are both broadly consistent with related shares for the sample period. Variations to the latter parameter value are found to be hardly relevant for the estimations (implying nearly identical posterior mode estimates) and for the quantitative results. The means of the stochastic processes, except for the price mark-up shock and the money supply/demand shocks, are set equals to one.

For the prior means, we refer, as far as possible, to estimates in previous studies. Specifically, the prior means for the parameters ϕ and ς which govern the degree of price and wage rigidity are set at 0.7. Regarding the fiscal policy rule (26), we follow Reicher (2013) and we set the debt feedback coefficient at 0.06 and coefficient on output at 0.01. The parameter of the interest rate rule (29) are set in a standard way, i.e. with a smoothing factor of 0.7, an inflation coefficient of 1.5 and an output coefficient of 0.01. Given that external information on the parameters of the banking cost function (17) were not available, we conducted estimates for a range of priors. For all experiments, including uninformative priors, we found small, but positive values for the two banking cost elasticities η^{rc} and $\omega\eta^{rc}$. In the estimation, summarized in Table 2, we therefore set the prior means of the Gamma distributions of the loan elasticities η^{rc} and ratio of the money-to-loan elasticity ω at 0.01 respectively 1 with appropriate prior distributions.

4.2 Data and shocks

For the estimation, we use quarterly data for the Euro area of nine time series from 1981Q1 to 2011Q4. Standard macroeconomic time series are taken from the AWM database. More specifically, we use real GDP growth, real private consumption growth, real investment growth, the private consumption deflator, wage inflation and the monetary policy interest rate (EONIA) to include the core of the workhorse DSGE model.[12] As a measure of central bank money, we employ the growth rate of total reserves.[13] We further use the growth rate of loans to the private sector and the mean adjusted interest spread between the lending rate and the monetary policy rate. Accordingly, we consider nine shocks to match the number of observable variables in the model. Seven macroeconomic shocks are in common with related studies: A time preference shock (ξ_t), a total factor productivity shock (a_t), an investment technology shock ($\epsilon_{x,t}$), a price mark-up shock ($\mu_{m,t}$), a wage mark-up shock ($\epsilon_{w,t}$), a government expenditure shock ($\epsilon_{g,t}$) and a policy rate shock ($\epsilon_{r,t}$). We further consider a shock to the banking cost function (ζ_t) and shocks to money demand, which are either measured by μ_t in version II or by $\epsilon_{ms,t}$ in version I. All shocks are modelled as AR(1) processes, except for shocks to the interest rate rule, which are assumed to be i.i.d. with zero mean. Note, that the shocks in the estimation relate to the first order approximation of the non-liner model relations. This implies a different scaling in comparison to other studies such as Smets and Wouters (2003), who apply a unit loading coefficient to most shocks.

4.3 Estimation

Employing Bayesian inference methods allows formalizing the use of prior information from earlier studies in estimating the parameters of a possibly complex DSGE model. This seems particularly appealing in situations where the sample period of the data is relatively short, as is the case for the Euro area. From a practical perspective, Bayesian inference may also help to alleviate the inherent numerical difficulties associated with solving the highly non-linear estimation problem.

Formally, let $p(\theta|m)$ denote the prior distribution of the parameter vector $\theta \in \Theta$ for some model $m \in M$, and let $L(Y_T|\theta, m)$ denote the likelihood function for the observed data, $Y_T = \{y_t\}_{t=1}^{T}$, conditional on parameter vector θ and model m. The joint posterior distribution of the parameter vector θ for model m is then obtained by combining the likelihood function for Y_T and the prior distribution of θ,

$$p(\theta|Y_T, m) \propto L(Y_T|\theta, m)p(\theta|m).$$

Table 2 shows the posterior mode estimates of the three model versions of the model (I, II and

[12] Since the model does not explain any divergences in trend growth rates of the variables, the growth rates of the observables are centered around zero. For the interest rates we deduct a linear trend.

[13] The time series for total reserves starts in 1999q1 only. We make use of missing data techniques (Giordani, Pitt, and Kohn, 2011). All estimations were conducted using dynare (Adjemian, Bastani, Karamé, Juillard, Maih, Mihoubi, Perendia, Ratto, and Villemot, 2011)

III).[14] The estimates of all parameters shared with related studies, specifically the degree of price and wage rigidity, are in line with previous estimates (see Smets and Wouters (2003)). For the estimation of the parameter values for the banking costs function, i.e. the elasticities of banking costs with regard to loans η_{rc} and the ratio of the reserve elasticity to the latter ω, we applied a prior 0.01 for η_{rc} and a prior of one for ω, while allowing for a considerably flat distribution. For the unrestricted estimation of the model, we found small positive values for both elasticities η_{rc} and $\omega\eta_{rc}$ (version I), indicating that banking costs are only slightly affected by loan and money, which are nevertheless non-separable according to these estimates. When the parameter ω is restricted to be zero (version II), the estimates lead to a much larger values – compared to version I – for the investment adjustment cost parameter γ_X, while the other parameter values are very similar to the estimates for version I. Notably, the standard deviation of the banking cost shock, which will be further analyzed below, is 2.5-times larger in version II than in the version I. Overall, we find that the unrestricted version is slightly preferred by the data, as indicated by the log data density.

5 Quantitative results

In this Section, we examine quantitative properties of the model. In the first part of this Section, we briefly discuss selected unconditional moments generated by the model. In the second part, we present some impulse response functions for shocks related to financial intermediation (the full set of impulse response functions is given in the Appendix A.4). In the third part of this Section, we examine the contribution of these shocks to the fluctuations of macroeconomic aggregates and prices.

5.1 Selected moments

Table 3 presents standard deviations of the observable variables and their contemporaneous correlations with output. These unconditional second moments are based on the data and on simulated series of all versions of the model (I, II, and III). For all versions, the standard deviations of the simulated series (except for loan growth) tend to overpredict the empirical standard deviations, to an extend comparable to Smets and Wouters's (2007) result for US data of a similar time period. All model based correlations with output of versions I and II accord qualitatively and most of them also quantitatively to the empirical correlations. A positive correlation of wage growth to gdp growth can however only be reproduced by version III. The overall performance (in terms of second moments) of version III, which has been estimated with pre-crisis data, is comparable to version I.

[14] Table 7 in Appendix A.3 shows the estimation results for the posterior distribution.

Table 2: Parameter estimates of the model with unrestricted parameters (version I), with the restriction $\omega = 0$ (version II), and for pre-2007 data (version III)

Parameter		Prior			Posterior mode		
		Type	*Mean*	*Std*	I	II	III
Price rigidity	ϕ	B	0.700	0.2000	0.7622	0.7647	0.8004
Wage rigidity	ϱ	B	0.700	0.2000	0.7741	0.7543	0.7802
Price indexation	ι	B	0.300	0.0200	0.1944	0.2226	0.1902
Investment adjustment cost	γ_X	G	6.000	5.0000	4.1783	7.6862	4.9534
Loan elasticity	η^{rc}	G	0.010	0.0070	0.0051	0.0051	0.0051
Money-to-loan elasticity	ω	G	1.000	0.7000	0.0421	–	0.0440
Policy							
Interest rate smoothing	ρ_r	B	0.700	0.1000	0.9014	0.8726	0.8975
Inflation coefficient	ρ_π	G	1.500	0.2000	1.6758	1.6333	1.6383
Output coefficient	ρ_y	G	0.010	0.0010	0.0097	0.0097	0.0098
Debt coefficient	τ_b	G	0.060	0.0100	0.0552	0.0572	0.0560
Output coefficient	τ_y	G	0.010	0.0050	0.0063	0.0063	0.0064
Shock persistence							
Preference shock	ρ_ξ	B	0.700	0.1000	0.8954	0.8780	0.9024
Technology shock	ρ_a	B	0.700	0.1000	0.9463	0.9428	0.9362
Investment shock	ρ_x	B	0.700	0.1000	0.8804	0.8648	0.8602
Mark-up shock prices	ρ_p	B	0.700	0.1000	0.9582	0.9359	0.9526
Mark-up shock wages	ρ_w	B	0.700	0.0500	0.6417	0.6633	0.6490
Banking cost shock	ρ_ζ	B	0.700	0.1000	0.9260	0.8126	0.8890
Money demand shock	ρ_m	B	0.700	0.1000	0.9383	0.8996	0.9412
Government spending shock	ρ_g	B	0.700	0.1000	0.8964	0.8940	0.8893
Standard deviations							
Preference shock	σ_ξ	G^{-1}	0.050	0.5000	0.0259	0.0278	0.0275
Technology shock	σ_a	G^{-1}	0.050	0.5000	0.0090	0.0092	0.0084
Interest rate shock	σ_r	G^{-1}	0.050	0.5000	0.1152	0.1177	0.1140
Investment shock	σ_x	G^{-1}	0.050	0.5000	0.0225	0.0393	0.0245
Price mark-up shock	σ_p	G^{-1}	0.050	0.5000	0.0133	0.0145	0.0156
Wages mark-up shock	σ_w	G^{-1}	0.050	0.5000	0.4702	0.3859	0.4990
Banking cost shock	σ_ζ	G^{-1}	0.500	5.0000	0.4290	1.1770	0.4390
Money demand shock	σ_m	G^{-1}	0.005	0.0500	0.0011	0.0207	0.0009
Government spending shock	σ_g	G^{-1}	0.025	0.2500	0.0076	0.0076	0.0079
log data density (Laplace appr.)					3450.22	3447.66	2927.74

Note: $\mathcal{B}, \mathcal{G}$ and $\mathcal{G}^{-1}$ correspond to Beta, Gamma and inverse Gamma distributions.

Table 3: Stylized facts

	Standard Deviation (σ_X)				Correlation with output growth ($\rho_{X,Y}$)			
	Data	I	II	III	Data	I	II	III
output growth	0.55	0.85	0.78	0.84	1.00	1.00	1.00	1.00
consumption growth	0.50	0.72	0.73	0.73	0.87	0.87	0.86	0.87
investment growth	1.51	2.89	2.59	2.76	0.88	0.81	0.74	0.80
total reserves growth	1.77	2.65	2.70	2.82	0.26	0.34	0.25	0.33
loan growth	0.96	1.60	1.57	1.60	0.96	0.54	0.48	0.58
CPI inflation	0.45	0.67	0.69	0.65	-0.31	-0.26	-0.30	-0.27
wage inflation	0.43	0.61	0.61	0.63	0.29	-0.01	-0.00	0.03
policy rate	1.60	2.85	2.95	2.91	-0.33	-0.10	-0.11	-0.09
lending rate	1.34	0.67	0.76	0.69	-0.42	-0.15	-0.11	-0.14

5.2 Impulse responses

In this Section, we examine responses to macroeconomic shocks for the version I and II. All shocks refer to one standard deviation of the estimated processes for the exogenous variables and Figure 1 shows responses to a positive innovation to the policy rate rule (29), which accords to a shock that is typically considered as the monetary policy shock. Overall, the responses for both versions, I and II, are very similar, except for the response of total reserves and loans, which decline in a more pronounced way in version I. The contractionary effects on output, consumption, loans, inflation, and the policy rate correspond to monetary policy effects in standard macroeconomic models.[15] Further, changes in the policy rate are passed through almost one-for-to other interest rates one in version II, whereas the impact responses of the loan rate, the deposit rate, and the bond rate are dampened (by roughly 20%) when reserves affects banking costs (in version I).

The Figures 2 and 3 show responses to shocks to money demand, which either enter the money demand condition (22) as disturbances $\epsilon_{md,t}$ in version I or shift the ratio of reserves to deposits μ_t in version II. In version I (see Figure 2), they affect reserves, real activity, prices, and interest rates to a similar magnitude. In contrast, money shocks lead to a substantial response of reserves in version I (see Figure 3), while other macroeconomic variables are almost unaffected. Nonetheless, these shocks to are not exactly irrelevant for the allocation, as the minimum reserve requirement affects activities of banks via their balance sheet.

Figures 4 show that banking cost shocks lead to a substantial increase in total reserves in version I and exert a contractionary effect on real activity and prices, which are much less pronounced than the reserve response. By strongly increasing their holdings of reserves, banks are able to

[15] Given that wages are more rigid than prices, the initail decline in the price level is more pronounced that the decline in the nominal wage, such that the wage rate slightly increases in the first periods.

partially offset the adverse impact of banking cost shocks in the version I, such that the interest rates, prices, and real activity react only to a small extent. In contrast, shifts in banking costs affect all macroeconomic variables at a similar magnitude in version II, including reserves (the right hand scale refers to version II).

Impulse responses to other shocks typically considered in the literature, namely, total factor productivity (tfp) shocks, price and wage mark-up shocks, and demand shocks, show a similar pattern (see Appendix A.4). Overall, the responses of the components of aggregate demand, of the inflation rate, and of the wage rate (qualitatively) relate to responses in standard models (e.g. Smets and Wouters (2007)). Responses of financial variables mostly share the signs of the deviations from steady state, but can differ with regard to the magnitude. In particular, responses of reserves as well as of the loan rate and the deposit rate are less pronounced when central bank money holdings affect banking costs (version I).

5.3 Variance decomposition

The variance decomposition of main macroeconomic variables for the versions I and II are given in the Tables 4 and 5. We first examine the shock contributions to the variance of macroeconomic variables (measured in growth rates) for version I (see Table 4). Preference shocks are most relevant for the variance of consumption and further contribute strongly to output, inflation, the policy rate, and the lending rate. Tfp shocks contribute particularly strongly to the variance of loans, the policy rate, and the lending rate, and to a much smaller extent to the components of aggregate demand, which relates to the findings in Smets and Wouters (2003). Shocks to the investment technology contribute most to the investment variance and further explain a large share of the variance of output, inflation, the policy rate, and the lending rate. The largest contributors to the variance of output are the wage and the price mark-up shocks, both being further responsible for large shares of the variance of investment, consumption, reserves, inflation, wages, the policy rate, and the lending rate.[16] Shocks to the interest rate rule, which are as usual interpreted as money policy shocks, are responsible for much smaller shares of macroeconomic fluctuations. Their contribution to the variance of output, consumption, investment, and inflation is comparable to the contribution of tfp shocks, while the tfp contribution to policy rate and lending rate variations is more than twice as large. This clearly differs from the more important role of interest rate shocks in Smets and Wouters (2003), where the policy rate is assumed to have a direct impact on private sector decision (as it governs the marginal rate of intertemporal substitution).

Turning to the shocks that immediately affect the financial markets, we find that banking cost shocks are hardly relevant for the variance of any macroeconomic variable, except for the

[16] This property, i.e. that shocks to the labor market play a major role for macroeconomic fluctuations, is a well-known and critically discussed feature shared with many related studies, and can be mitigated by applying more elaborate specifications of the labor market, as in Smets, Wouters and Gali (2011).

Table 4: Variance decomposition with non-separable money (I)

Forecast horizon: ∞									
Variable	Shock Contribution								
	ε_ξ	ε_a	ε_x	ε_r	ε_p	ε_w	ε_ζ	ε_m	ε_g
output growth	15.01	8.21	14.02	5.98	23.61	23.04	0.01	8.52	1.60
consumption growth	41.54	7.87	1.95	6.05	18.09	16.04	0.01	8.39	0.07
investment growth	5.90	5.05	41.69	3.21	18.81	20.49	0.01	4.82	0.03
reserves growth	4.94	1.20	0.96	2.07	20.82	14.27	54.36	1.37	0.01
loan growth	8.18	45.26	9.29	2.20	27.50	3.21	0.02	3.49	0.86
CPI inflation	10.02	7.93	12.82	5.09	26.22	25.03	0.01	12.80	0.08
wage inflation	1.49	1.83	4.65	0.82	40.41	49.14	0.02	1.62	0.02
policy rate	13.79	11.66	12.54	5.36	19.85	22.83	0.01	13.88	0.08
lending rate	15.71	13.26	14.26	3.62	23.05	26.14	1.83	2.04	0.09

variance of reserves. This accords to the impulse response functions, which show that reserves are adjusted to a relatively large amount when banking costs shocks hit the economy (see Figure 4). Shocks to money demand contribute significantly to the variances of all variables listed in Table 4, and in particular for inflation and the policy rate. Notably, they appear to provide a larger contribution to macroeconomic fluctuations than shocks to the monetary policy rule (29), which is highly suggestive for an important role of the market for reserves for monetary policy and macroeconomic dynamics. Finally, we find that government spending shocks play a minor role for macroeconomic fluctuations (except for the variances of output).

Table 5 presents variance decompositions for the version of the model where the elasticity of banking costs with regard to money is restricted to equals zero, $\omega = 0$ (version II). The contribution of non-financial shocks to macroeconomic volatility is comparable to version I. A notable difference is that the contribution of investment adjustment shocks to the policy rate is now much higher than in version I (and seems to compensate for the contribution of money demand shocks). The most apparent differences between both versions refer to the financial shocks, namely, shocks to the policy rate, banking costs shocks, and money demand shocks. Compared to version I, policy rate shocks play an even smaller role for the variance of all macroeconomic variables, except for the lending rate. Like in version I, banking costs shocks are negligible for the volatility of most macroeconomic variables. However, they now significantly affect the variance of the loan rate, while they are negligible for the variance of reserves, which is an obvious implication of the property that banking costs are independent of reserves ($\omega = 0$) in version II. Money demand shocks, i.e. shocks to the minimum reserve requirement, only contribute to the fluctuations in reserves, implying a de facto irrelevance for other macroeconomic variables.

Table 6 further presents variance decompositions for version III. Overall, the results are

Table 5: Variance decomposition for the version with separable money (II)

Forecast horizon: ∞									
Variable	Shock Contribution								
	ε_ξ	ε_a	ε_x	ε_r	ε_p	ε_w	ε_ζ	ε_m	ε_g
output growth	21.60	8.68	19.60	4.18	21.31	22.73	0.03	0.00	1.87
consumption growth	49.27	8.04	3.17	5.11	17.19	17.14	0.02	0.00	0.07
investment growth	5.60	4.43	60.52	1.02	13.03	15.35	0.02	0.00	0.03
reserves growth	4.57	0.97	1.39	0.42	17.79	13.07	0.00	61.79	0.00
loan growth	10.67	49.77	11.33	1.03	23.82	2.28	0.21	0.00	0.88
CPI inflation	11.33	8.45	18.93	2.92	30.34	27.87	0.07	0.00	0.08
wage inflation	1.63	1.74	7.59	0.40	39.80	48.77	0.06	0.00	0.02
policy rate	14.35	11.64	22.71	4.78	21.02	25.38	0.03	0.00	0.09
lending rate	13.63	11.05	21.57	4.52	20.39	24.28	4.48	0.00	0.09

closely related to the results of version I. A main difference to the latter is that wage mark-up shocks contribute less to the variance of all macroeconomic variables than price mark-up shocks, except for the wage rate. Further, shocks to money demand are now slightly less relevant, though they nevertheless contribute more to fluctuations in macroeconomic variables than interest rate shocks (like in version I). Given that these shocks also substantially contribute to macroeconomic dynamics in the pre-crisis periods, their relevance does not only originate from larger disturbances in the market for central bank money, which has been witnessed in the post-2007 period.

Figures 10-11 further show the observed decomposition of output over the sample period for versions I and II. Most apparently, shocks to banks' demand for reserves, namely, μ_t in version II and $\epsilon_{md,t}$ in version I, play a non-negligible role for output fluctuations in version I (see Figure 10), in particular in the post-2007 period. In contrast, money demand shocks are entirely irrelevant in the version II, where a larger contribution to output dynamics is assigned to shocks to investment adjustment costs. These figures further confirm that banking costs shocks are irrelevant in both versions for output growth over the entire sample period (including the post-2007 period). Figures 12 and 13 present the observe variable decomposition for total reserve growth. Looking through the lens of version I, changes in reserves are to a large extent driven by banking costs shocks and, in particular, during the last part of the sample. We view this as a reasonable pattern, since turbulences in the financial sector starting with the US subprime crisis , which in our model would be manifested in shifts in banking costs, have likely led banks to adjust their holdings of liquid assets, including central bank money. In contrast, fluctuations in reserves in version II (see Figure 13) are largely explained by innovations to the ratio between deposits and reserves (μ_t), whereas banking cost shocks are irrelevant for the variance of reserves in the entire sample period.

Table 6: Variance decomposition for the non-separable money version with pre-2007 data (III)

Forecast horizon: ∞									
Variable	Shock Contribution								
	ε_ξ	ε_a	ε_x	ε_r	ε_p	ε_w	ε_ζ	ε_m	ε_g
output growth	17.70	5.57	16.09	5.94	24.93	20.80	0.01	7.14	1.82
consumption growth	44.98	5.14	2.08	5.99	19.52	15.30	0.00	6.93	0.05
investment growth	5.84	3.63	45.74	3.18	19.68	17.79	0.01	4.12	0.02
reserves growth	5.21	0.66	1.47	2.13	21.37	12.48	55.69	0.98	0.01
loan growth	9.79	41.95	10.82	2.34	27.91	3.01	0.03	3.19	0.97
CPI inflation	12.46	6.43	10.22	3.87	30.83	25.97	0.01	10.14	0.07
wage inflation	1.47	1.03	4.09	0.63	38.45	53.18	0.01	1.12	0.01
policy rate	16.65	8.34	10.73	5.59	24.12	23.70	0.01	10.79	0.07
lending rate	18.46	9.23	11.90	3.86	27.27	26.41	1.20	1.59	0.08

6 A counterfactual analysis for money shocks

As shown in the previous Section, shocks to money demand in the version I of the model substantially contribute to the variance of macroeconomic variables and, in particular, to the variance of the policy rate R_t^m (see Table 4). These shocks are typically neglected in related studies where medium scale macroeconomic models are estimated with Bayesian techniques (e.g. Smets and Wouters (2003)). In these models, variations in the policy rate are typically viewed as being sufficiently captured by an interest rate feedback rule (like 29), while central bank money is ignored. In our model, we additionally account for the fact that the policy rate clears the market for central bank money. Given that we identify the policy rate with the overnight interbank rate (EONIA), these money shocks essentially summarize unexplained components of the interbank rate that are not captured by banks' aggregate demand for money as specified in the model. This might however suggest that money shocks account for the difference between the rate that is actually set by the (European) central bank, i.e. the main refinancing rate, and the applied overnight interbank rate.

Figure 14 displays three interest rates: the policy rate as explained by our model (dark blue dashed-dotted line), the empirical rate for the main refinancing operations MRO (green dashed line), and a counterfactual rate (light blue solid line) that is computed without money shocks. Consider first the sample period prior to 2007. If money shocks mainly explained the difference between the EONIA and the main refinancing rate, the counterfactual rate would be following closely the main refinancing rate, or would at least be closer to the latter than to the EONIA. Yet, this is obviously not the case, as the solid line is in some periods closer to the EONIA and in others closer to the main refinancing rate. Thus, money shocks do not simply account for differences between the rate set by the central bank and the overnight interbank rate. In fact, the spread between the model implied rate (EONIA) and the counterfactual rate is sometimes close to nil, e.g.

between 2004 and 2006, whereas in the period between 2001 and 2004 the spread is permanently positive. Thus, money demand shocks provide a systematic contribution to changes in the demand for money and for the market clearing rate, which are neither explained by non-financial shocks, nor by shocks to the interest rate rule or by shocks to banking costs.

For the last part of the sample starting with 2007, Figure 14 shows pronounced deviations of the counterfactual rate from the EONIA rate and also from the MRO rate. This period is characterized by high money holdings (see 12) and initially increasing interest rates, where the counterfactual rate is lying below the money implied rate and the main refinancing rate. The increase in money holdings is largely driven by banking costs shocks, implying ceteris paribus a lower market clearing rate for reserves, and more specifically a lower rate than observed in the data. The model accommodates the joint appearance of increasing policy rates and high money demand by positive money demand shocks, increasing the banks' valuation of money. In contrast, a further exogenous increase in banking costs, which could in principle serve for the same purpose, would simultaneously lead to a further increase in the loan rate that is, however, not consistent with the data.

7 Conclusion

In this paper, we aim assessing the informational content of banking activities and changes in reserves for macroeconomic dynamics, which have typically been neglected in medium scale macroeconomic models build for estimation purposes. Thus, in contrast to previous studies which examine the role of money for real activity and inflation, we focus on a narrow monetary aggregate (total reserves) rather than broader aggregates (like M1 or M2), which are typically found to be negligible. We estimate different versions of the model applying Bayesian estimation techniques for Euro area data, including reserves, bank loans, and interest rates on bank loans (in addition to commonly applied macroeconomic time series). The estimations indicate that banking costs are affected by credit supply and reserve holdings, indicating that (high powered) money matters for real activity and prices. Shocks to the banks' demand for reserves contribute significantly to other macroeconomic variables, while fluctuations in reserves are mainly induced by exogenous shifts of banking costs. While the latter shocks are hardly relevant for variations in real activity and prices, disturbances to money demand did play an important role for the fluctuations in output, inflation, and, most of all, in the policy rate. Specifically, money demand shocks helped to reconcile changes in reserves in the most recent part of the sample with the prevailing policy rate.

By introducing open market operations and a role of central bank money in affecting banks'cost of credit provision in an estimated model we have extended scope of possible analysis of monetary policy. We view this framework as a particularly suited for the analysis of recent ECB balance sheet policies, which is beyond the scope of this paper.

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A Appendix

A.1 Equilibrium conditions

Definition 1 *A rational expectations equilibrium is a set of sequences* $\{c_t,\ \lambda_t,\ n_t,\ d_t,\ \pi_t,\ w_t,\ \widetilde{w}_t,\ mc_t,\ k_t,\ x_t,\ q_t,\ \eta_t,\ m_t,\ pb_t,\ pb_t^T,\ l_t,\ i_t,\ \tilde{Z}_t,\ y_t,\ s_t,\ R_t^m,\ R_t^L,\ R_t^d,\ R_t^b,\ R_t,\ \varphi_{t,t+1},\ p_t^B,\ b_t^T, g_t, \widetilde{\tau}_t\}_{t=0}^{\infty}$, *satisfying*

$$\Xi_{m,t} = -\left(R_t^m - 1\right) - \epsilon_{md,t},\ \textit{if}\ \omega > 0 \quad \textit{or} \quad i_t + m_{t-1}\pi_t^{-1} = \mu_t d_t \pi_{t-1}^{-1} \quad \textit{if}\ \omega = 0, \tag{31}$$

$$1/E_t R_{t+1}^B = 1/R_t^d - E_t\left(R_{t+1}^m - 1\right)\mu_{t+1}\varphi_{t,t+1}, \tag{32}$$

$$\xi_t u_{c,t} = \lambda_t, \tag{33}$$

$$1/R_t^d = E_t\left[\varphi_{t,t+1}\left(1 + u_{d,t+1}/u_{c,t+1}\right)\right], \tag{34}$$

$$\varphi_{t,t+1} = \left(\beta/\pi_{t+1}\right)\left(\lambda_{t+1}/\lambda_t\right), \tag{35}$$

$$1/R_t = E_t\varphi_{t,t+1}, \tag{36}$$

$$\mu_{p,t} w_t = \left(R_t/R_t^L\right) mc_t \alpha a_t n_t^{\alpha-1} k_{t-1}^{1-\alpha}, \tag{37}$$

$$l_t/R_t^L = w_t n_t, \tag{38}$$

$$w_t = [\varsigma w_{t-1}^{1-\varepsilon_n}\left(\pi_t/\pi_{t-1}\right)^{\varepsilon_n - 1} + (1-\varsigma)\widetilde{w}_t^{1-\varepsilon_n}]^{1/(1-\varepsilon_n)}, \tag{39}$$

$$f_t^1 = f_t^2,\ \textit{where}\ f_t^1 = \widetilde{w}_t \xi_t u_{c,t}\left(w_t/\widetilde{w}_t\right)^{\varepsilon_n} n_t + E_t\beta\varsigma[\left(\pi_{t+1}/\pi_t\right)\left(\widetilde{w}_{t+1}/\widetilde{w}_t\right)]^{\varepsilon_n - 1} f_{t+1}^1, \tag{40}$$

$$\textit{and}\ f_t^2 = \epsilon_{w,t}\nu\xi_t\mu_w\left(w_t/\widetilde{w}_t\right)^{(1+\upsilon)\varepsilon_n} n_t^{(1+\upsilon)} + \beta\varsigma[\left(\pi_{t+1}/\pi_t\right)\left(\widetilde{w}_{t+1}/\widetilde{w}_t\right)]^{(1+\upsilon)\varepsilon_n} f_{t+1}^2,$$

$$\tilde{Z}_t = [\varepsilon/\left(\varepsilon - 1\right)]Z_t^1/Z_t^2,\ \textit{where}\ Z_t^1 = \xi_t c_t^{-\sigma} y_t mc_t + \phi\beta E_t\left(\pi_{t+1}/\pi_t^{\iota}\right)^{\varepsilon} Z_{t+1}^1 \tag{41}$$

$$\textit{and}\ Z_t^2 = \xi_t c_t^{-\sigma} y_t + \phi\beta E_t\left(\pi_{t+1}/\pi_t^{\iota}\right)^{\varepsilon-1} Z_{t+1}^2,$$

$$1 = (1-\phi)(\tilde{Z}_t)^{1-\varepsilon} + \phi\left(\pi_t/\pi_{t-1}^{\iota}\right)^{\varepsilon-1}, \tag{42}$$

$$s_t = (1-\phi)\tilde{Z}_t^{-\varepsilon} + \phi s_{t-1}\left(\pi_t/\pi_{t-1}^{\iota}\right)^{\varepsilon}, \tag{43}$$

$$k_t = (1-\delta)k_{t-1} + \epsilon_{x,t}\left(1 - \left(\gamma_X/2\right)\left(\left(x_t/x_{t-1}\right) - 1\right)^2\right)x_t, \tag{44}$$

$$1 = q_t\epsilon_{x,t}\left(1 - \left(\gamma_X/2\right)\left(\left(x_t/x_{t-1}\right) - 1\right)^2 - \gamma_X\left(\left(x_t/x_{t-1}\right) - 1\right)x_t/x_{t-1}\right) + \beta E_t\left[\left(\lambda_{t+1}/\lambda_t\right)q_{t+1}\epsilon_{x,t+1}\gamma_X\left(\left(x_{t+1}/x_t\right) - 1\right)\left(x_{t+1}/x_t\right)^2\right], \tag{45}$$

$$q_t = \beta E_t\left(\lambda_{t+1}/\lambda_t\right)\left[q_{t+1}(1-\delta) + \left(mc_{t+1}/\mu_{p,t+1}\right)(1-\alpha)a_{t+1}n_{t+1}^{\alpha}k_t^{-\alpha}\right], \tag{46}$$

$$1/R_t^d = 1 - E_t\left(R_{t+1}^m - 1\right)\left(1 - \mu_{t+1}\right)\varphi_{t,t+1} \tag{47}$$

$$1/R_t^L = 1/R_t^d - E_t\varphi_{t,t+1}\mu_{t+1}\left(R_{t+1}^m - 1\right) - \Xi_{l,t}, \tag{48}$$

$$d_t = m_t + E_t p_{t+1}^B b_t + l_t, \tag{49}$$

$$i_t = m_t - m_{t-1}\pi_t^{-1}, \tag{50}$$

$$pb_t = pb_t^T - m_{t-1}, \tag{51}$$

$$pb_t^T = p_t^B b_{t-1}^T, \tag{52}$$

$$R_t^b = \rho p_t^B/(p_{t-1}^B - 1), \tag{53}$$

$$y_t = a_t n_t^{\alpha} k_{t-1}^{1-\alpha}/s_t, \tag{54}$$

$$y_t = c_t + x_t + g_t + \Xi_t, \tag{55}$$

(where $u_{c,t} = [c_t - hc_{t-1}]^{-\sigma}$, $u_{d,t} = \varrho d_t^{-\varphi}$, $\Xi_t = \zeta_t[l_t\left(m_{t-1}\pi_t^{-1} - \mu d_{t-1}\pi_t^{-1} + i\right)^{-\omega}]^{\eta_{rc}}$, $\Xi_{l,t} = \eta_{rc}\ \Xi_t/l_t$, $\Xi_{m,t} = -\omega\eta_{rc}\Xi_t\left(m_{t-1}\pi_t^{-1} - \mu d_{t-1}\pi_t^{-1} + i\right)^{-1}$*), as well as the transversality conditions, fiscal*

and monetary policy satisfying

$$\widetilde{\tau}_t = g_t - \left(p_t^B - 1\right)\rho^{-1} b_t^T + p_t^B b_{t-1}^T/\pi_t, \tag{56}$$

$$\widetilde{\tau}_t - \widetilde{\tau} = g_t - g + \rho_{\tau b} \cdot \left(p_t^B b_{t-1}^T \pi_t^{-1} - \overline{pb}^T \pi^{-1}\right) + \rho_{\tau y} \cdot (y_t - y), \tag{57}$$

$$R_t^m = \left(R_{t-1}^m\right)^{\rho_R} (R^m)^{1-\rho_R} (\pi_t/\pi)^{\rho_\pi(1-\rho_R)} (y_t/y)^{\rho_y(1-\rho_R)} \exp \varepsilon_{r,t}, \tag{58}$$

and $\overline{pb}^T > 0$, $\overline{\pi} \geq \beta$, *for given initial values* $m_{-1} > 0$, $l_{-1} > 0$, $pb_{-1}^T > 0$, $pb_{-1} > 0$, $k_{-1} > 0$, $x_{-1} > 0$, $\pi_{-1} > 0$, *and* $s_{-1} \geq 1$, *and* $\{\xi_t,\ a_t,\ g_t,\ \mu_{p,t},\ \epsilon_{w,t}\ ,\ \epsilon_{x,t},\ \zeta_t\}_{t=0}^{\infty}$ *and* $\{\epsilon_{ms,t}\}_{t=0}^{\infty}$ *or* $\{\epsilon_{md,t}\}_{t=0}^{\infty}$ *satisfying*

$$\xi_t = \rho_\xi \xi_{t-1} + \left(1 - \rho_\xi\right) + \varepsilon_{\xi,t}, \tag{59}$$

$$a_t = \rho_a a_{t-1} + (1 - \rho_a) + \varepsilon_{a,t}, \tag{60}$$

$$g_t - g = \rho_g \left(g_{t-1} - g\right) + \varepsilon_{g,t}, \tag{61}$$

$$\mu_{p,t} = \rho_p \mu_{p,t-1} + \left(1 - \rho_p\right) \mu_p + \varepsilon_{p,t}, \tag{62}$$

$$\epsilon_{w,t} = \rho_w \epsilon_{w,t} + (1 - \rho_w) + \varepsilon_{w,t}, \tag{63}$$

$$\epsilon_{x,t} = \rho_x \epsilon_{x,t-1} + (1 - \rho_x) + \varepsilon_{x,t}, \tag{64}$$

$$\zeta_t = \rho_\zeta \zeta_{t-1} + \left(1 - \rho_\zeta\right) + \varepsilon_{\zeta,t}, \tag{65}$$

$$\mu_t = \rho_\mu \mu_{t-1} + \left(1 - \rho_\mu\right) \mu + \varepsilon_{\mu,t} \ \textit{if}\ \eta_t > 0, \tag{66}$$

$$\textit{or}\ \epsilon_{md,t} = \rho_{md} \epsilon_{md,t-1} + \varepsilon_{md,t} \ \textit{if}\ \eta_t = 0,$$

and i.i.d. mean zero innovations $\varepsilon_{\xi,t}$, $\varepsilon_{a,t}$, $\varepsilon_{r,t}$, ε_{gt}, $\varepsilon_{p,t}$, $\varepsilon_{w,t}$, $\varepsilon_{x,t}$, $\varepsilon_{\zeta,t}$, *and* $\varepsilon_{ms,t}$ *or* $\varepsilon_{md,t}$.

A.2 Steady state 3

In this Appendix, we examine the deterministic steady state of the economy. Variables without a time index denote the particular steady state values. Consider a competitive equilibrium as given in definition 1. It can easily be shown that the equilibrium conditions (33)-(55) imply the steady state values $\{c,\ n,\ d,\ \pi,\ w,\ \widetilde{w},\ mc,\ k,\ x,\ q,\ m,\ pb,\ pb^T,\ l,\ i,\ \tilde{Z},\ y,\ s,\ R^L,\ R^d,\ R^b,\ R,\ p^B,\ \eta\}$ to satisfy $\overline{pb}^T = pb^T$, $\overline{\pi} = \pi$,

$$R = \pi/\beta,\ k\delta = x,\ q = 1,\ 1/\beta = (1 - \delta) + (mc/\mu_p)(1 - \alpha) n^\alpha k^{-\alpha}, \tag{67}$$

$$\nu n^\upsilon = \mu_w^{-1} \widetilde{w} \left((1 - h)c\right)^{-\sigma},\ w = \widetilde{w},\ \text{where}\ \ \mu_w = \varepsilon^w/(\varepsilon^w - 1) \tag{68}$$

$$l/R^L = wn,\ mc\alpha n^{\alpha-1} k^{1-\alpha} = \mu_p w \left(R^L/R\right), \tag{69}$$

$$u_d/u_c = (R/R^d) - 1,\ 1/R^d = 1 - (R^m - 1)(1 - \mu)(\beta/\pi), \tag{70}$$

$$1/R^L = 1/R^d - (\beta/\pi)\mu (R^m - 1) - \Xi_l, \tag{71}$$

$$d = m + pb + l,\ pb = pb^T - m, \tag{72}$$

$$i = m\left(1 - \pi^{-1}\right), \tag{73}$$

$$\tilde{Z} = \left(\frac{1 - \phi\pi^{(1-\iota)(\varepsilon-1)}}{1-\phi} \right)^{1/(1-\varepsilon)}, \; mc = \tilde{Z}\frac{\varepsilon - 1}{\varepsilon}\frac{1 - \phi\beta\pi^{(1-\iota)\varepsilon}}{1 - \phi\beta\pi^{(1-\iota)(\varepsilon-1)}}, \; s = \frac{1-\phi}{1 - \phi\pi^{\varepsilon(1-\iota)}}\tilde{Z}^{-\varepsilon}, \quad (74)$$

$$y = n^{\alpha} k^{1-\alpha}/s, \; y = c + x + g + \Xi, \quad (75)$$

$$\Xi_m = -(R^m - 1) - \epsilon_{md}, \text{ if } \eta = 0 \text{ or } i + m\pi^{-1} = \mu d\pi^{-1} \text{ if } \eta = 0, \quad (76)$$

$$1/R^B = 1/R^d - (R^m - 1)\,\mu(\beta/\pi), \; R^B = \rho p^B / \left(p^B - 1\right), \quad (77)$$

where $u_c = [c(1-h)]^{-\sigma}$, $u_d = \varrho d^{-\varphi}$, $u_n = -\nu n^{\upsilon}$, $\Xi = \zeta[l(m\pi^{-1} - \mu d\pi^{-1} + i)^{-\omega}]^{\eta_{rc}}$, $\Xi_l = \eta_{rc}\Xi/l$, and $\Xi_m = -\omega\eta_{rc}\Xi(m\pi^{-1} - \mu d\pi^{-1} + i)^{-1}$. The steady state allocation and the associated prices can be determined with the conditions (67)-(77) for given target values of inflation and real public debt. The debt target implies the steady state transfer to be adjusted in accordance with the consolidated public sector budget constraint (56), while the prevailing monetary policy instruments are chosen in a way that is consistent with the inflation target. Suppose that the central bank sets the inflation target $\overline{\pi}$ and the government set the debt target $\overline{pb}^T$, which satisfy $\overline{\pi} = \pi$ and $\overline{pb}^T = pb^T$. Then, the conditions in (74) directly determine the steady state values $\{\tilde{Z}, s, mc\}$ and the conditions in (67) imply that the steady state values $\{q, R, k/n, x/n\}$ are given by

$$R = \pi/\beta, \; q = 1, \; k/n = \left(\beta\left[mc/\mu_p\right](1-\alpha)/\left[1 - \beta(1-\delta)\right]\right)^{1/\alpha}, \; x/n = \delta k/n,$$

Using that aggregate production satisfies $y = n\,(k/n)^{1-\alpha}/s$ and substituting out y in the resource constraint (see 75), leads to

$$c + g + \Xi = [(k/n)^{1-\alpha} s^{-1} - \delta\,(k/n)]n, \quad (78)$$

The two conditions in (69) can further be combined to

$$l = \left[mc/\mu_p\right] \alpha n\,(k/n)^{1-\alpha} R, \quad (79)$$

Substituting out the real wage rate with $\nu n^{\upsilon} = \mu_w w\,[(1-h)c]^{-\sigma}$ (see 68) in $\left[mc/\mu_p\right]\alpha\left(\frac{k}{n}\right)^{1-\alpha} = w\left(R^L/R\right)$ (see 69), gives

$$\nu n^{\upsilon}\mu_w^{-1}\,[(1-h)c]^{\sigma} = \left[mc/\mu_p\right]\alpha\,(k/n)^{1-\alpha}\left(R/R^L\right). \quad (80)$$

The conditions in (73) and the steady state version of the banking costs function, further imply $\Xi(m,d,l,\pi) = \zeta\left(l\left(m\left(1+\Lambda^{-1}\right) - \mu d\pi^{-1}\right)^{-\omega}\right)^{\eta_{rc}}$, $\Xi_l(m,d,l,\pi) = \eta_{rc}\Xi/l$, and $\Xi_m(m,d,l,\pi) = -\omega\eta_{rc}\Xi\left(m\left(1+\Lambda^{-1}\right) - \mu d\pi^{-1}\right)^{-1}$. Equating deposit demand and supply (70), gives

$$1 + u_d/u_c = (\pi/\beta) - (R^m - 1)(1-\mu), \quad (81)$$

and combining $1/R^d = 1 - (R^m - 1)(1-\mu)(\beta/\pi)$ with (71) leads to $R/R^L = (\pi/\beta)(1-\Xi_l) - (R^m - 1)$. Using latter to eliminate R/R^L in (80), leads to

$$\nu n^{\upsilon} \mu_w^{-1} [(1-h)c]^{\sigma} = [mc/\mu_p]\, \alpha (k/n)^{1-\alpha} [(\pi/\beta)(1-\Xi_l) - (R^m - 1)] . \tag{82}$$

Further combining the conditions in (72), gives $d = pb^T + l$. Substituting out loans with the latter in (79) and the banking cost terms in (78), (81), and (82), the five steady state values $\{\mathbf{c}, \mathbf{n}, \mathbf{m}, \mathbf{d}, \mathbf{R}^m\}$ can <u>for $\omega > 0$</u> be determined by

$$\mathbf{c} + g = \left[(k/n)^{1-\alpha} s^{-1} - \delta (k/n) \right] \mathbf{n} - \Xi(\mathbf{m}, \mathbf{d}, \mathbf{d} - pb^T, \pi), \tag{83}$$

$$1 + \varrho \mathbf{d}^{-\varphi} [\mathbf{c}(1-h)]^{\sigma} = (\pi/\beta) - (\mathbf{R}^m - 1)(1-\mu), \tag{84}$$

$$\nu \mathbf{n}^{\upsilon} \mu_w^{-1} [(1-h)\mathbf{c}]^{\sigma} = [mc/\mu_p]\, \alpha (k/n)^{1-\alpha} \left[(\pi/\beta)(1 - \Xi_l(\mathbf{m}, \mathbf{d}, \mathbf{d} - pb^T, \pi)) - (\mathbf{R}^m - 1) \right], \tag{85}$$

$$\mathbf{d} - pb^T = [mc/\mu_p]\, \alpha \mathbf{n} (k/n)^{1-\alpha} (\pi/\beta), \tag{86}$$

$$\Xi_m(\mathbf{m}, \mathbf{d}, \mathbf{d} - pb^T, \pi) = -(\mathbf{R}^m - 1) - \epsilon_{md}, \tag{87}$$

indicating that reserves are non-separable from the equilibrium allocation. <u>For $\omega = 0$</u>, we can determine the steady state values $\{\mathbf{c}, \mathbf{n}, \mathbf{d}, \mathbf{R}^m\}$ by (84), (86),

$$\mathbf{c} + g = \left[(k/n)^{1-\alpha} s^{-1} - \delta (k/n) \right] \mathbf{n} - \Xi(\mathbf{d}, \mathbf{d} - pb^T, \pi),$$

$$\nu \mathbf{n}^{\upsilon} \mu_w^{-1} [(1-h)\mathbf{c}]^{\sigma} = [mc/\mu_p]\, \alpha (k/n)^{1-\alpha} \left[(\pi/\beta)(1 - \Xi_l(\mathbf{d}, \mathbf{d} - pb^T, \pi)) - (\mathbf{R}^m - 1) \right],$$

while reserves m can residually be determined by $m = \mu d \pi^{-1}$, indicating the separability of money. Notably, the minimum requirement ratio μ can affect the steady state allocation (see 84). Finally, (77) determines the bond rate and the bond prices.

A.3 Tables

Table 7: Posterior Distribution of parameter estimates of the model with unrestricted parameters (version I)

Parameter		Prior			Posterior distribution			
		Type	*Mean*	*Std*	mode	mean	5%	95%
Price rigidity	ϕ	B	0.700	0.2000	0.7622	0.7634	0.7164	0.8129
Wage rigidity	ϱ	B	0.700	0.2000	0.7741	0.7515	0.5960	0.8649
Price indexation	ι	B	0.300	0.0200	0.1944	0.2040	0.1428	0.2641
Investment adjustment cost	γ_X	G	6.000	5.0000	4.1783	5.7880	2.8213	8.7148
Loan elasticity	η^{rc}	G	0.010	0.0070	0.0051	0.0100	0.0006	0.0199
Money-to-loan elasticity	ω	G	1.000	0.7000	0.0421	0.0441	0.0249	0.0622
Policy								
Interest rate smoothing	ρ_r	B	0.700	0.1000	0.9014	0.9023	0.8821	0.9233
Inflation coefficient	ρ_π	G	1.500	0.2000	1.6758	1.7084	1.4980	1.9098
Output coefficient	ρ_y	G	0.010	0.0010	0.0097	0.0098	0.0082	0.0114
Debt coefficient	τ_b	G	0.060	0.0100	0.0552	0.0568	0.0398	0.0743
Output coefficient	τ_y	G	0.010	0.0050	0.0063	0.0084	0.0019	0.0146
Shock persistence								
Preference shock	ρ_ξ	B	0.700	0.1000	0.8954	0.8861	0.8474	0.9267
Technology shock	ρ_a	B	0.700	0.1000	0.9463	0.9439	0.9175	0.9708
Investment shock	ρ_x	B	0.700	0.1000	0.8804	0.8364	0.7476	0.9277
Mark-up shock prices	ρ_p	B	0.700	0.1000	0.9582	0.9485	0.9162	0.9820
Mark-up shock wages	ρ_w	B	0.700	0.0500	0.6417	0.6598	0.5201	0.8775
Banking cost shock	ρ_ζ	B	0.700	0.1000	0.9260	0.9259	0.8789	0.9771
Money demand shock	ρ_m	B	0.700	0.1000	0.9383	0.9335	0.9029	0.9650
Government spending shock	ρ_g	B	0.700	0.1000	0.8964	0.8936	0.8446	0.9438
Standard deviations								
Preference shock	σ_ξ	G^{-1}	0.050	0.5000	0.0259	0.0263	0.0223	0.0303
Technology shock	σ_a	G^{-1}	0.050	0.5000	0.0090	0.0092	0.0081	0.0102
Interest rate shock	σ_r	G^{-1}	0.050	0.5000	0.1152	0.1168	0.1035	0.1299
Investment shock	σ_x	G^{-1}	0.050	0.5000	0.0225	0.0317	0.0169	0.0468
Price mark-up shock	σ_p	G^{-1}	0.050	0.5000	0.0133	0.0143	0.0101	0.0186
Wages mark-up shock	σ_w	G^{-1}	0.050	0.5000	0.4702	0.5183	0.0674	0.9306
Banking cost shock	σ_ζ	G^{-1}	0.500	5.0000	0.4290	0.4500	0.2750	0.6170
Money demand shock	σ_m	G^{-1}	0.005	0.0500	0.0011	0.0011	0.0010	0.0012
Government spending shock	σ_g	G^{-1}	0.025	0.2500	0.0076	0.0077	0.0069	0.0087

Note: $\mathcal{B}, \mathcal{G}$ and $\mathcal{G}^{-1}$ correspond to Beta, Gamma and inverse Gamma distributions. The distribution is based on 500 000 draws and the acceptance rate is 24.22%.

A.4 Figures

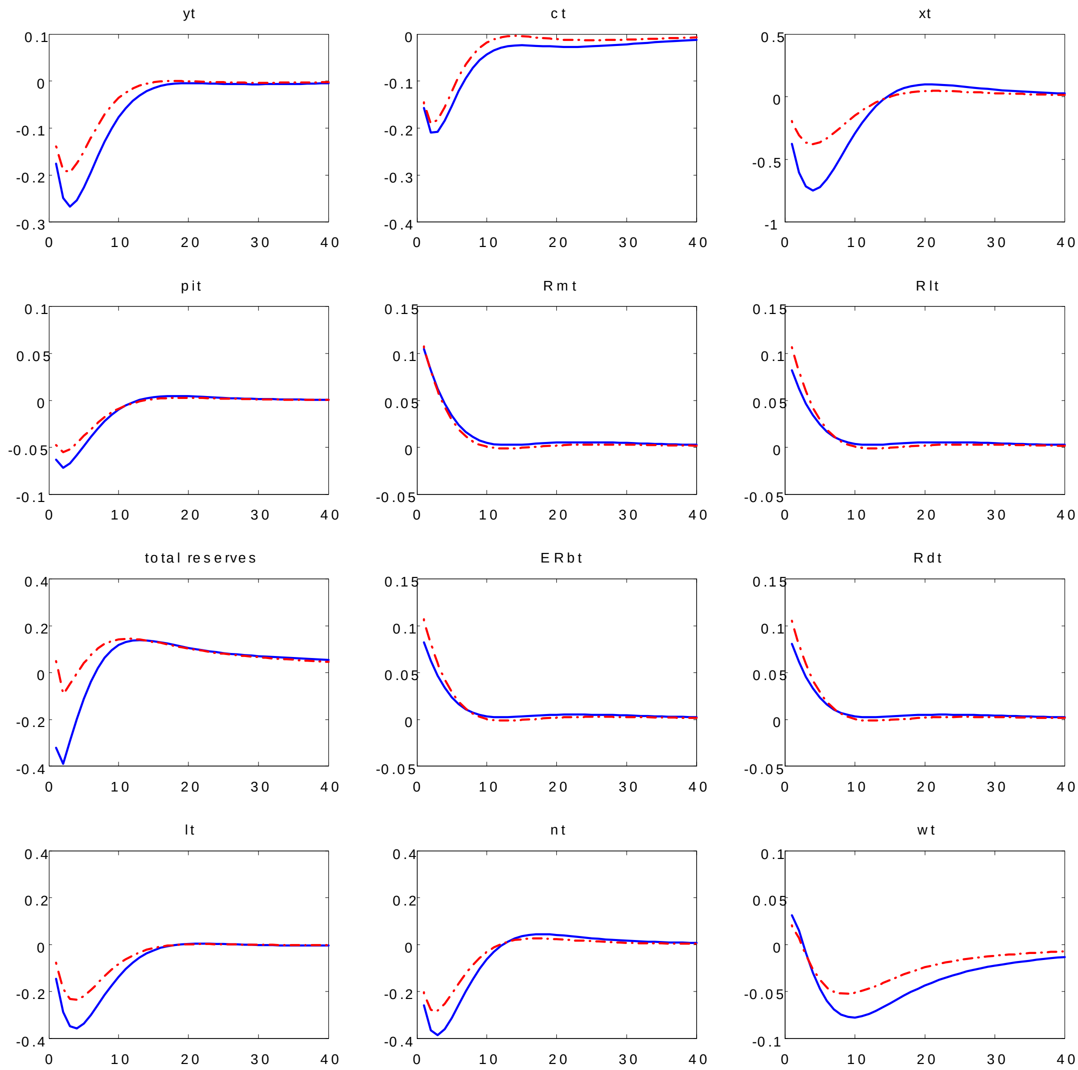

Figure 1: Impulse responses to an interest rate shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

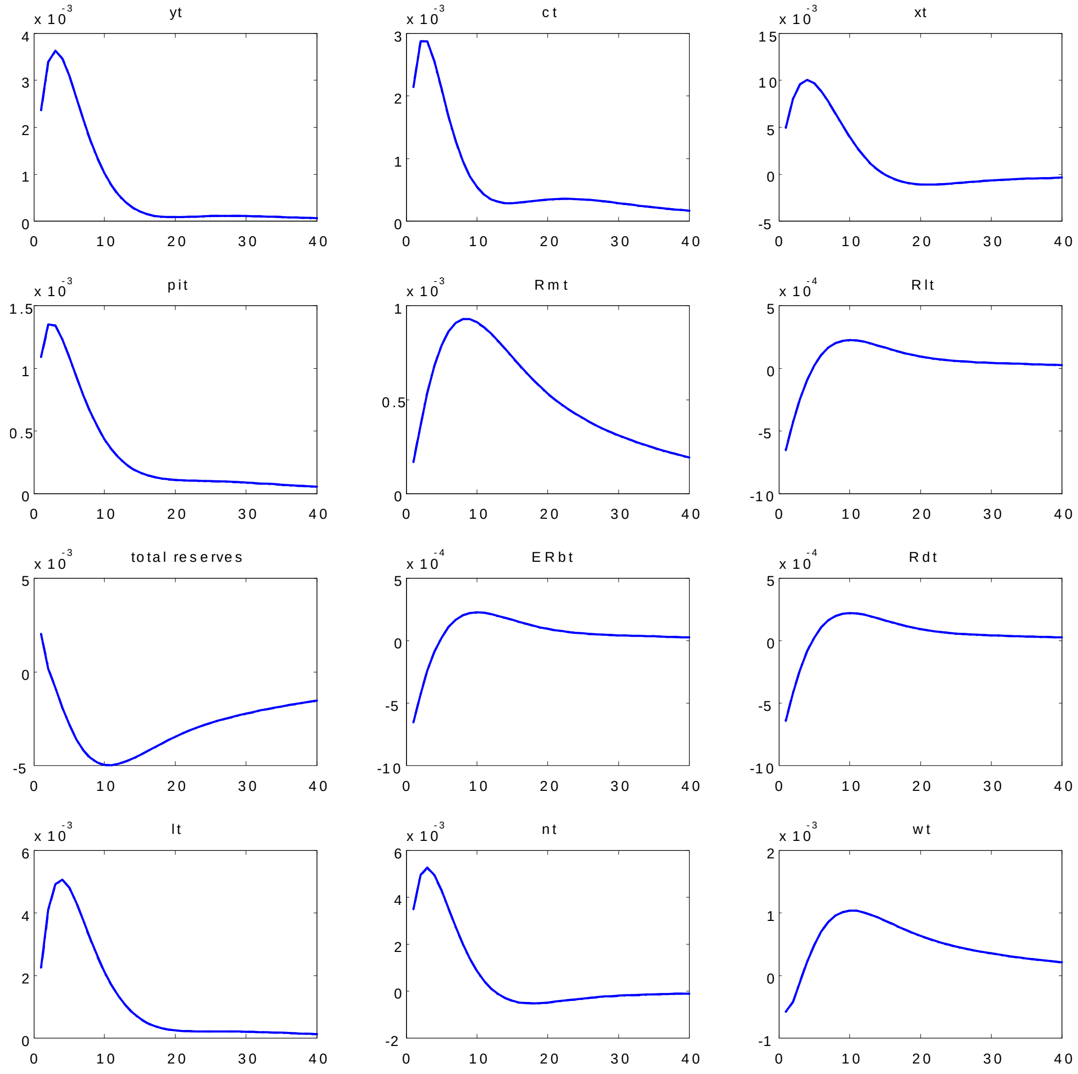

Figure 2: Impulse responses to a money supply/demand shock (in percent deviations from steady state; version I)

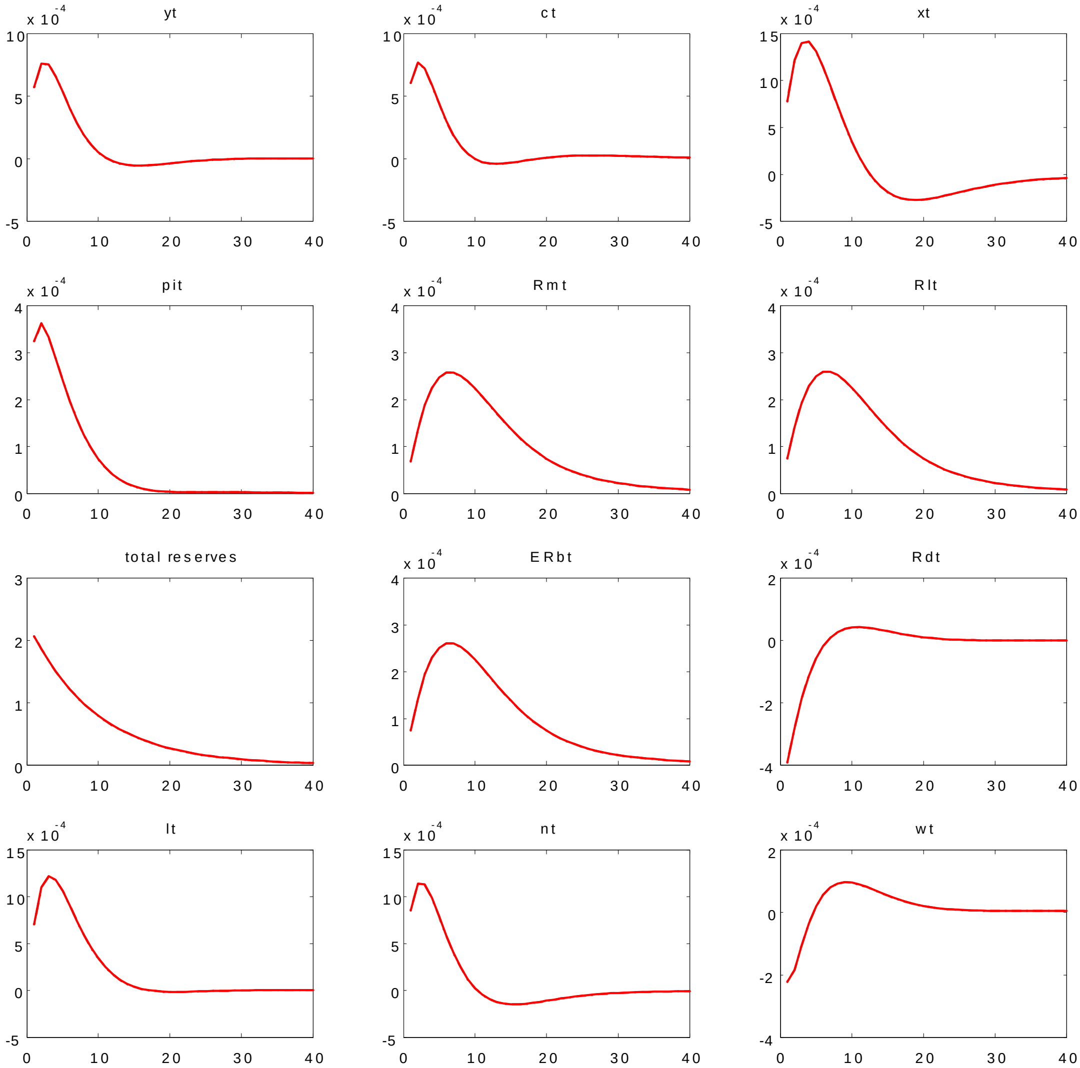

Figure 3: Impulse responses to a money supply/demand shock (in percent deviations from steady state; version II)

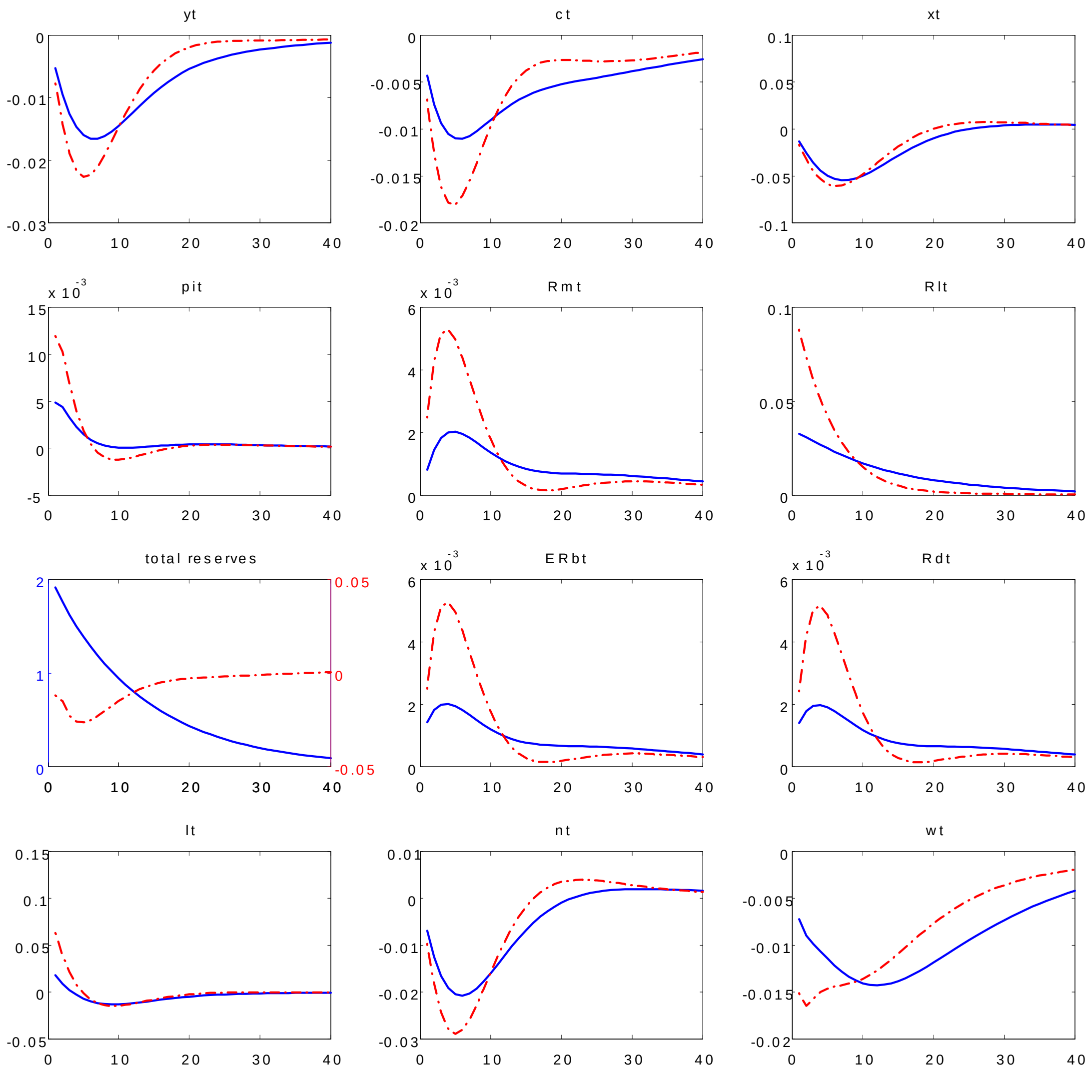

Figure 4: Impulse responses to a banking cost shock (in percent deviations from steady state)

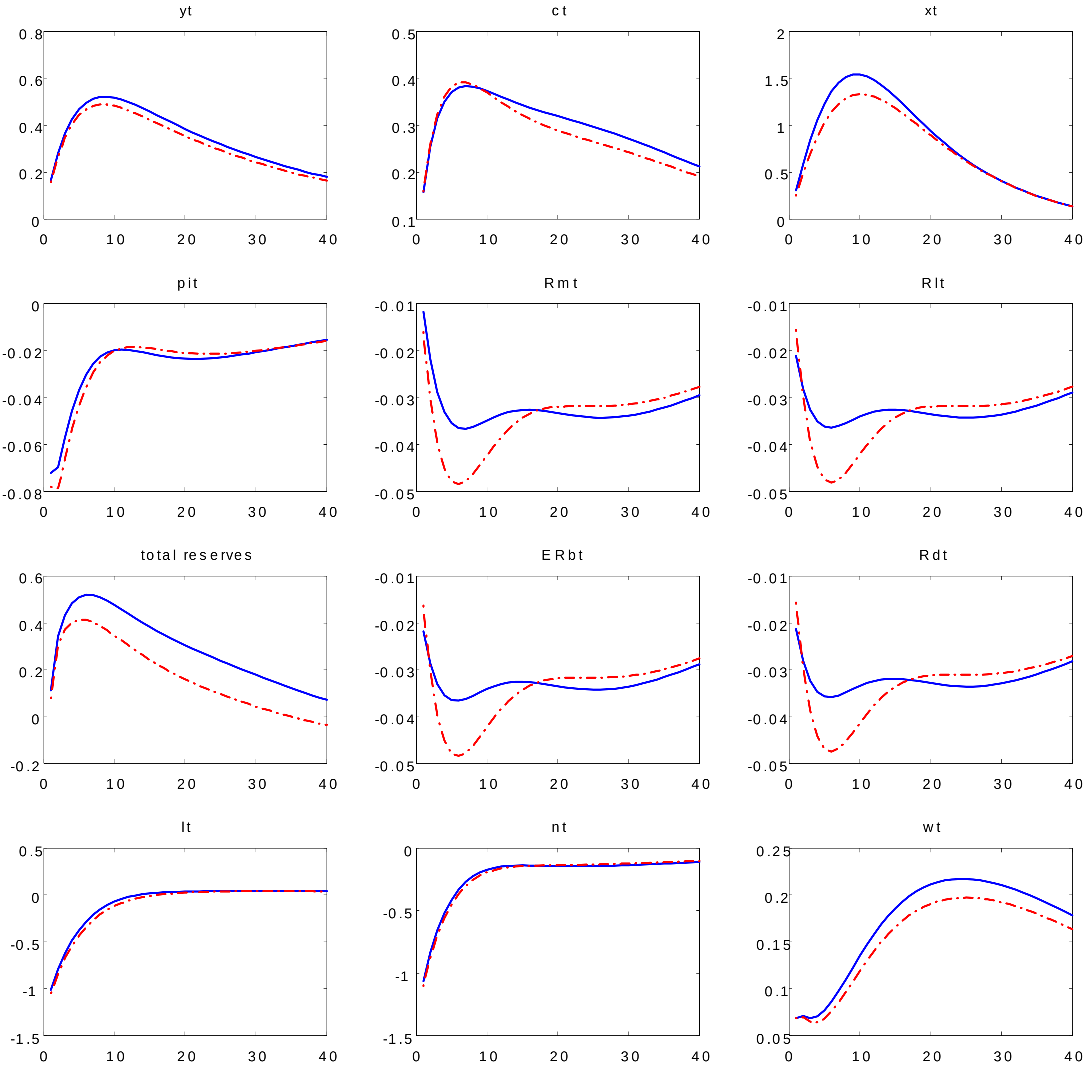

Figure 5: Impulse responses to a productivity shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

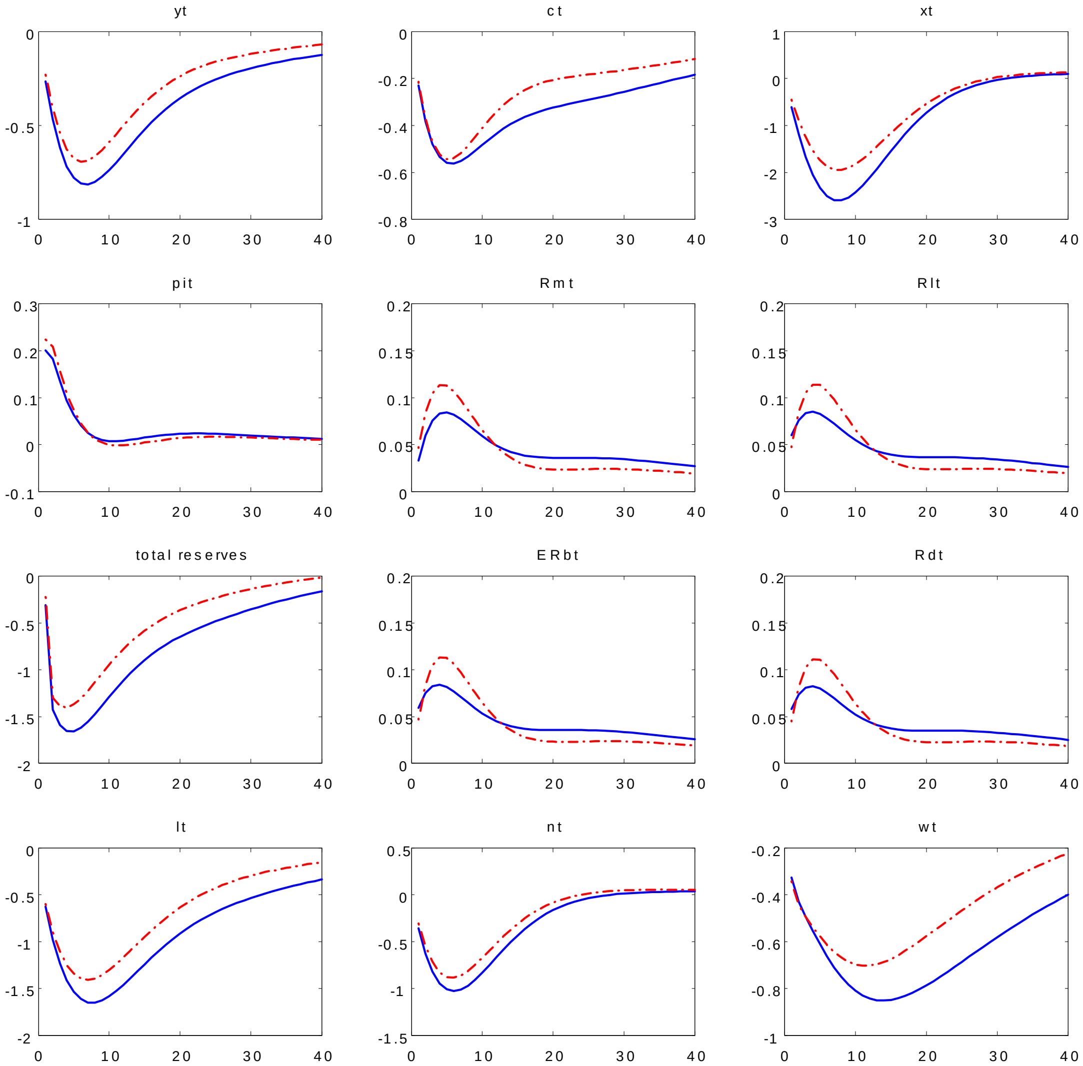

Figure 6: Impulse responses to a price mark-up shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

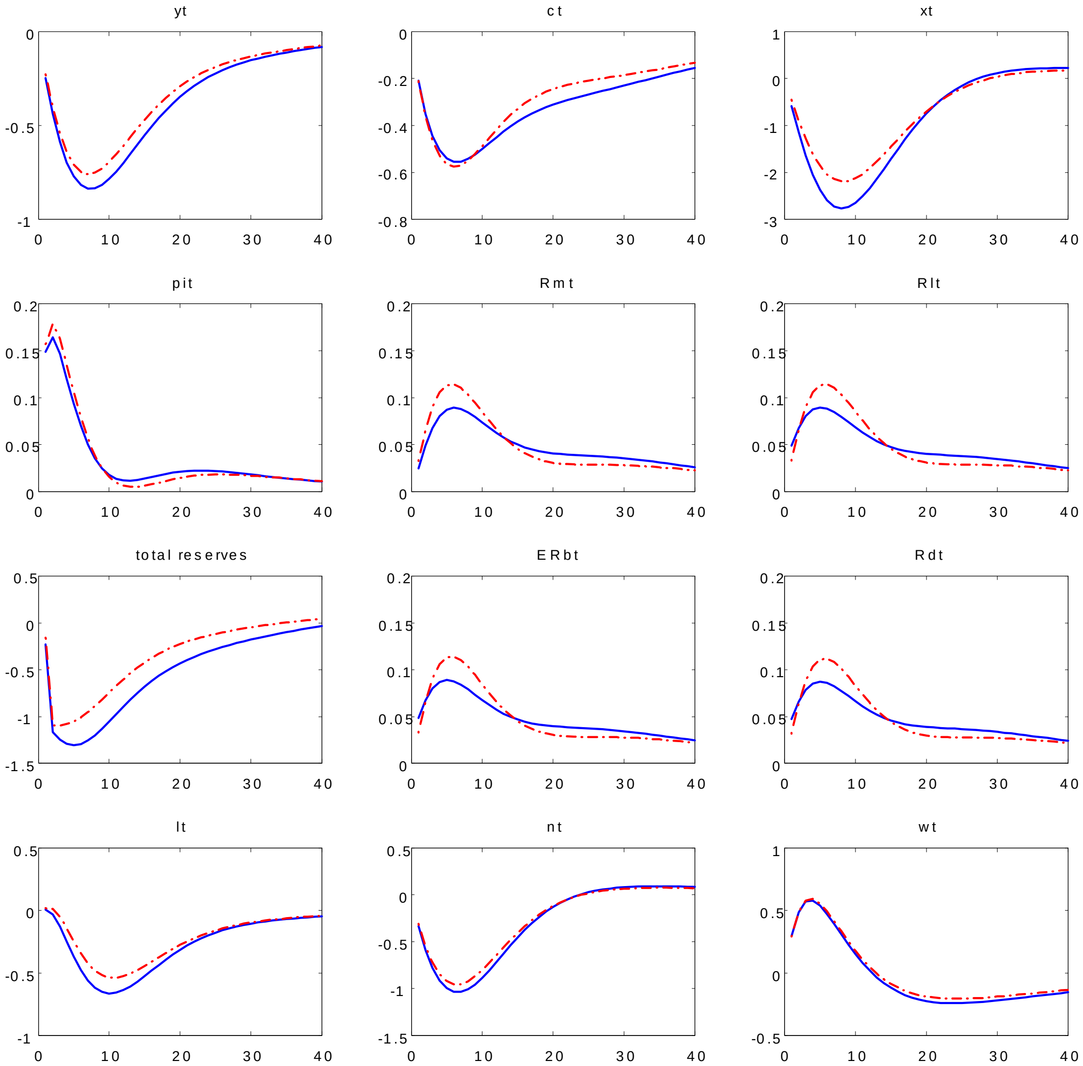

Figure 7: Impulse responses to a wage mark-up shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

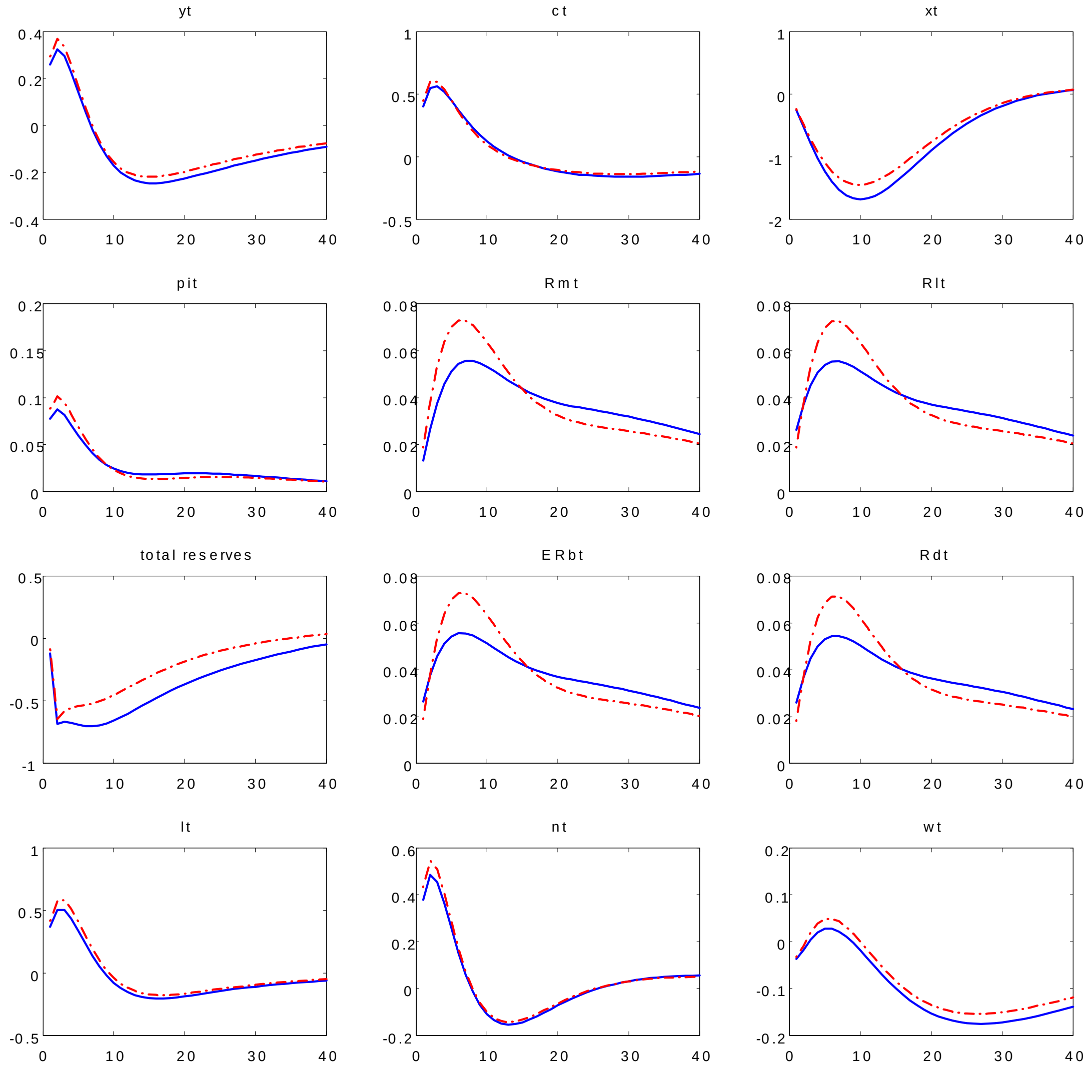

Figure 8: Impulse responses to a prefercence shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

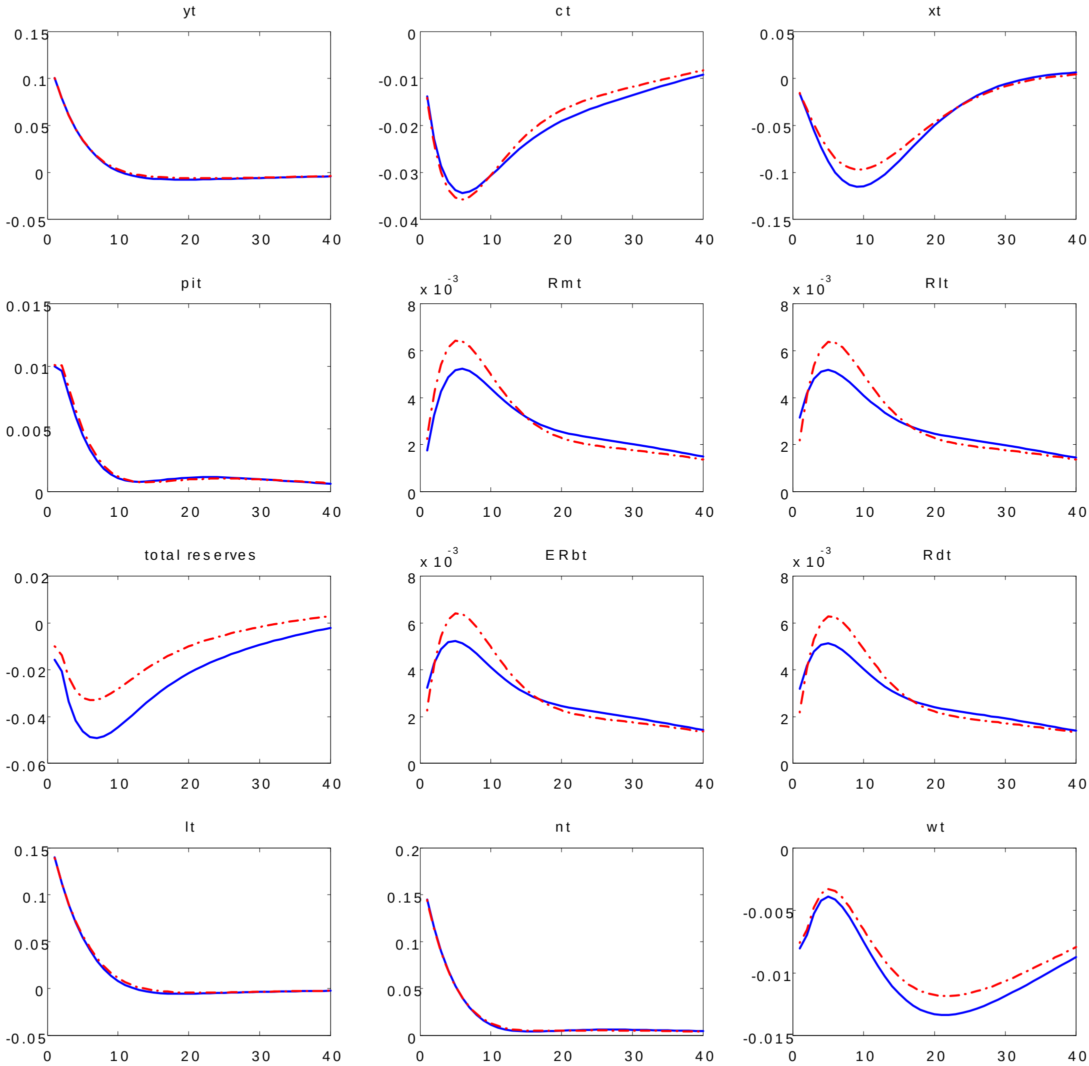

Figure 9: Impulse responses to a government spending shock (in percent deviations from steady state; version I: blue line, version II: red dashed line)

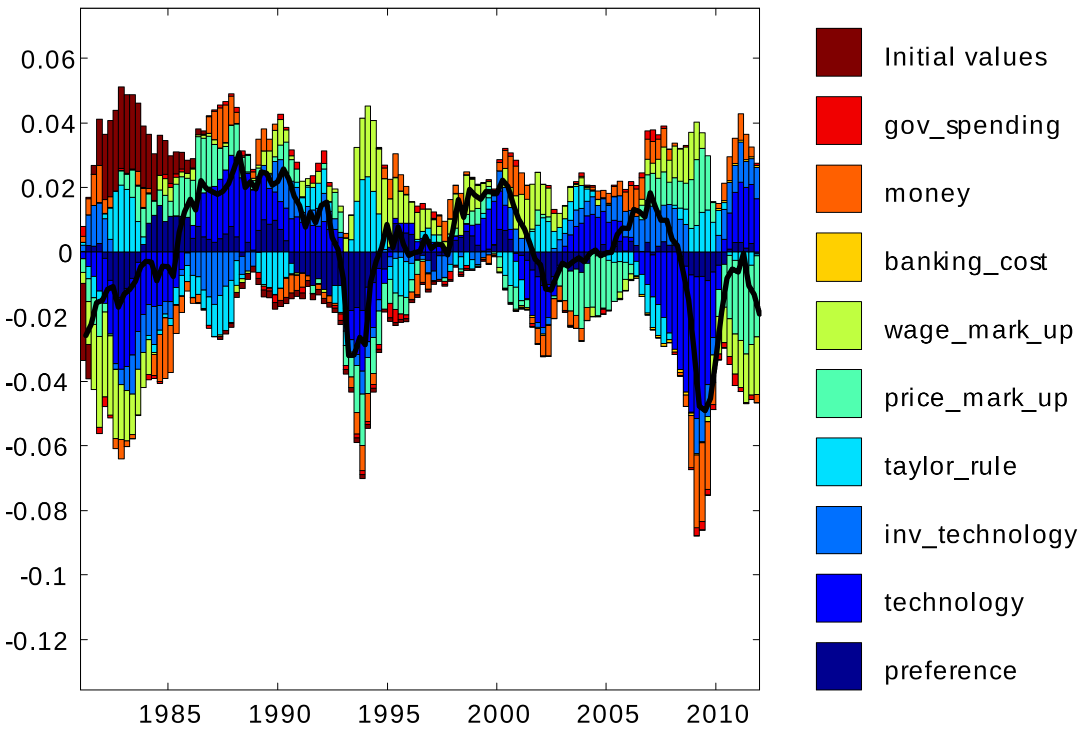

Figure 10: Variance decomposition of output growth for version I

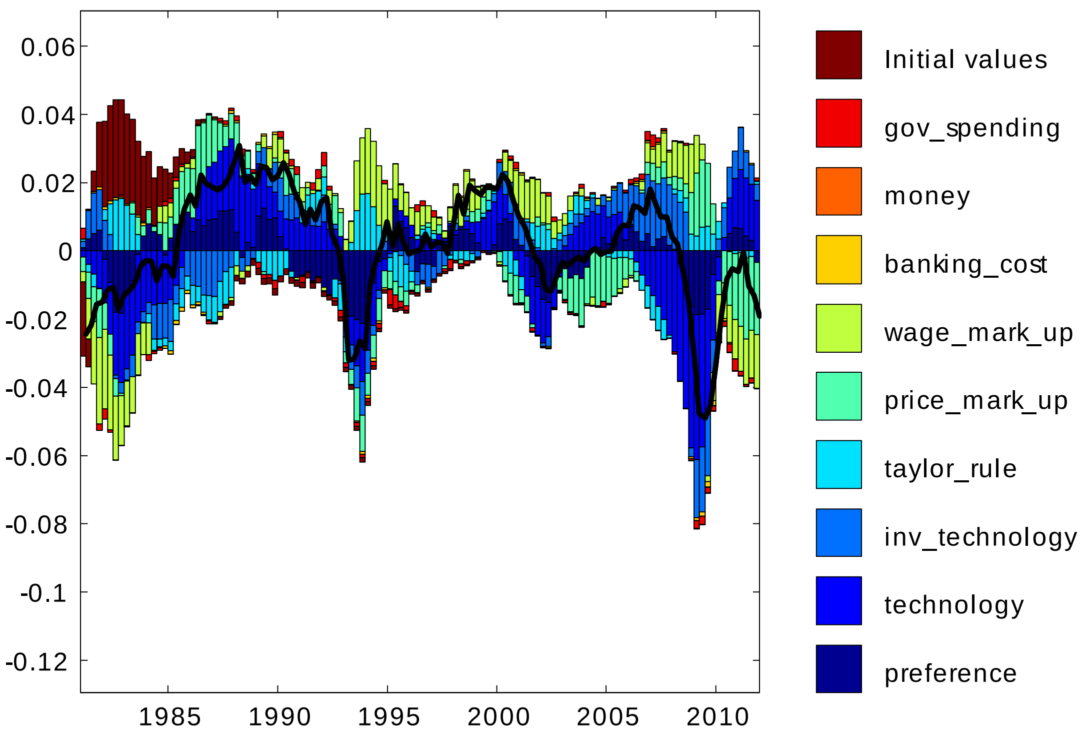

Figure 11: Variance decomposition of output growth for version II

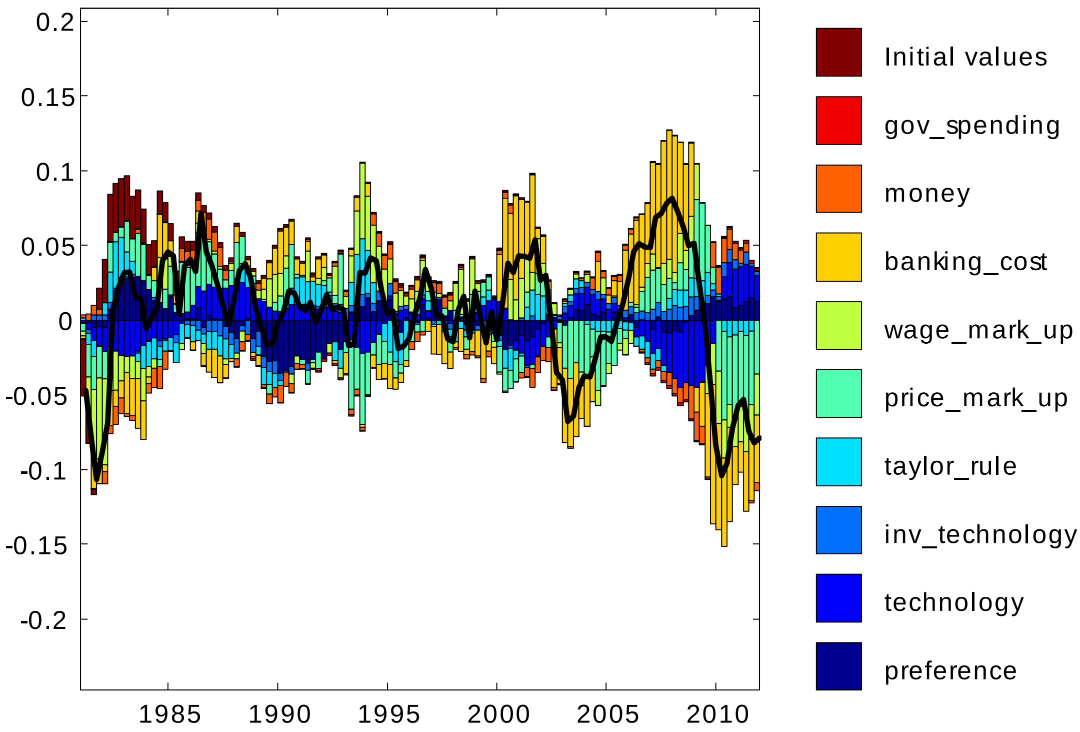

Figure 12: Variance decomposition of total reserve growth for version I

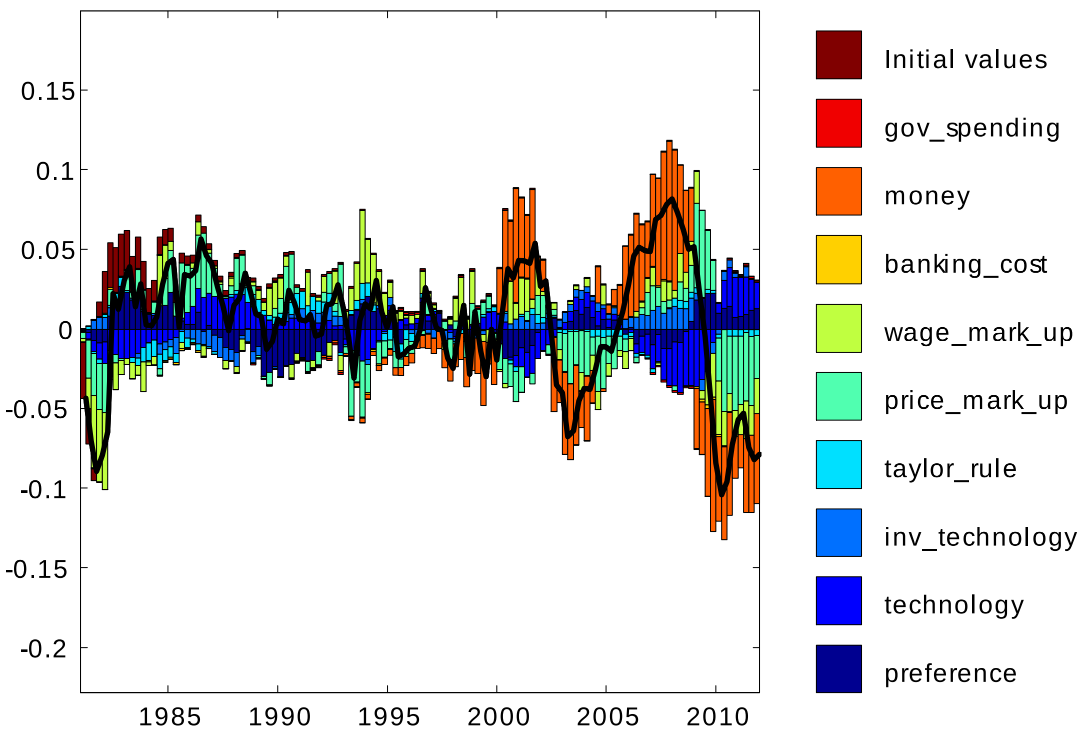

Figure 13: Variance decomposition of total reserve growth for version II

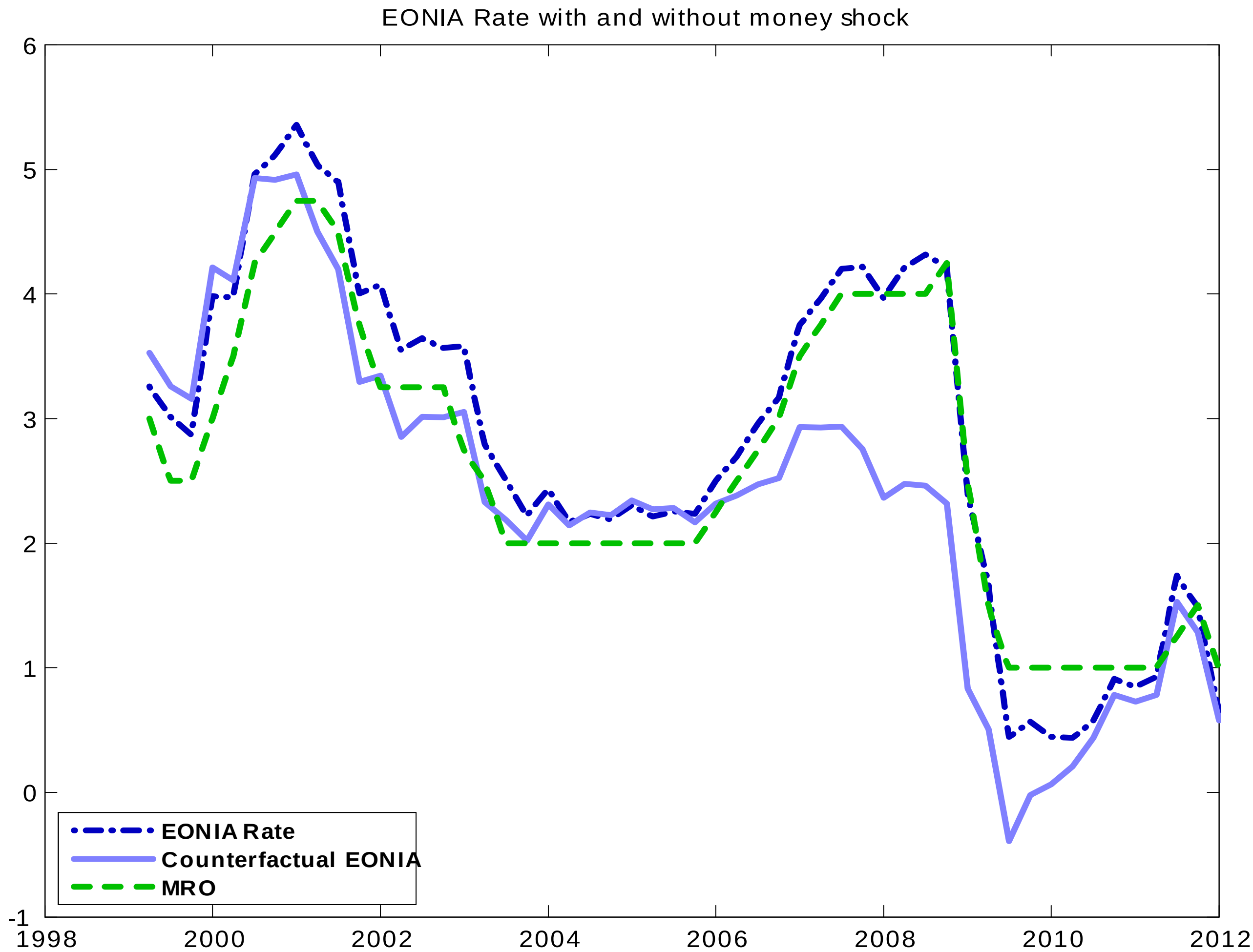

Figure 14: Counterfactual series for the policy rate without money demand shocks for version I (compared to model fitted EONIA and empirical main refinancing rate)