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Liquidity provision as a monetary policy tool: the ECB's non-standard measures after the financial crisis

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Abstract

We study the macroeconomic consequences of the money market tensions associated with the financial crisis in the euro area. In a structural VAR, we identify a liquidity shock rooted in the interbank market and use its impulse response functions to calibrate key parameters of a Smets and Wouters (2003) closed-economy model augmented with a banking sector à la Gertler and Kiyotaki (2010). We highlight two main results. First, an identified liquidity shock causes a sizable and persistent fall in investment. The shock can account for one third of the observed, large fall in euro area aggregate investment in 2008–09. Second, the liquidity injected in the market by the ECB played an important role in attenuating the macroeconomic impact of the shock. According to our counterfactual simulations based on the structural model, in the absence of ECB liquidity injections interbank spreads would have been at least 200 basis points higher and their adverse impact on investment would have been more than twice as severe.

JEL classification: E44, E58

Keywords: ECB, euro area, financial crisis, financial frictions, interbank market, non-standard monetary policy

Non-Technical Summary

In response to the Global Financial Crisis of 2008-09, many central banks adopted non-standard monetary policy responses. Given the financial structure of the euro area, where banks are the primary source of credit to the economy, the non-standard measures implemented by the ECB focused on repairing the bank lending channel in order to prevent a credit crunch. The ECB adapted its existing monetary policy framework and started providing liquidity to bank counterparties on a large scale. This included the granting of full and unlimited access to liquidity at a fixed rate and the expansion of maturities at which liquidity was offered. The ECB replaced private intermediation and became an important source of funding for financial intermediaries.

The aim of this paper is to provide a quantitative assessment of the impact of these liquidity measures on the economy at large. The paper proceeds in two steps.

In the first step, we empirically investigate the causal link between the interbank market tensions and the economic recession without imposing strong theoretical restrictions. The results of this analysis suggest that interbank liquidity shocks led to a large increase in bank lending spreads and to a sizable fall in private investment.

In the second step, we use a theoretical model to shed light on the transmission mechanism of liquidity shocks to the macroeconomy. The model accounts for banks' ability to obtain funding through both retail deposits and interbank deposits. Malfunctioning in the interbank market can drive up bank lending rates and, as result, lead to reductions in credit to the economy and in aggregate investment. The model illustrates how the provision of liquidity by the central bank at market interest rates can reduce the adverse consequences of a financial crisis on investment: central bank interventions allow liquidity-constrained banks to continue financing firms with good investment opportunities, even if cash-rich banks are unable or unwilling to lend on the interbank market.

To study the macroeconomic effects of the liquidity injections by the ECB, we compute the counterfactual scenario that would have been observed, had non-standard measures not been implemented. The results of this exercise suggest that the tensions in the euro area money market were a major determinant of the dynamics of investment during the Great Recession—investment being the component of the national accounts which was most heavily affected by the recession. The liquidity injected by the ECB played an important role in attenuating the macroeconomic impact of the money market tensions. Without such an intervention, interbank spreads would have been at least 200 basis points higher and their adverse impact on investment would have been more than twice as severe.

1 Introduction

The financial crisis in the euro area had its outset in summer 2007 as tensions in money markets emerged world-wide and spreads between secured and unsecured money market rates rose. The interbank spread in the euro area—as shown in Figure 1—was quoted at 8 basis points on average before the crisis, but it increased by more than 60 basis points in the second half of 2007. The filing for bankruptcy of Lehman Brothers in September 2008 aggravated this development as interbank spreads reached almost 200 basis points in response. These tensions produced severe malfunctionings, and at times a complete dry-up of the interbank market. Asymmetric information and time-varying perceptions of counterparty risk made cash-rich banks unwilling to lend to banks with liquidity shortages. Illiquid banks, even if healthy and solvent, faced the risk of being forced into bankruptcy. Moreover, negative externalities on the real economy in the form of asset fire sales or a credit crunch became a threat. In the Great Recession of 2009–10, GDP fell by 5 percent, most heavily driven by a decline in aggregate investment of about 15 percent.

The crisis motivated aggressive monetary policy responses. The ECB interventions were tailored to address the money market malfunctioning and ultimately support banks' provision of credit. Large amounts of liquidity were provided to financial institutions, subject to adequate collateral, through various repo operations with different maturities.[1] The interventions were successful in restoring liquidity in the interbank market, especially during the financial crisis (2008–2010) and, in specific countries, during the sovereign debt crisis (2011–2013)—see Garcia-de-Andoan et al. (2016). It is however less clear whether the ECB's liquidity provision had a broader macroeconomic impact.

The objective of our paper is to provide a quantitative assessment of such macroeconomic impact. In doing so, we proceed in two steps. In the first step, we empirically investigate the causal link between the interbank market tensions and the economic recession in a structural VAR, which allows us to draw inference from the data without imposing strong theoretical restrictions. The result of this analysis suggests that structural liquidity shocks rooted in the interbank market lead to a sizable increase in bank lending spreads and to a sizable fall in private investment. The effects of

[1] Lenza et al. (2010) provide an overview on how the ECB reacted to the financial crisis and compare its non-standard measures with the policies conducted by the US Federal Reserve and the Bank of England.

the shock were more muted on other national account variables and on inflation.

In the second step, we use a DSGE model to shed light on the likely transmission mechanism of liquidity shocks to the macroeconomy. More specifically, we extend the Smets and Wouters (2003) closed-economy model with a characterisation of the interbank market based on Gertler and Kiyotaki (2010). The interbank market is characterised by an agency problem à la Gertler and Karadi (2011). In the model, the provision of large amounts of liquidity by the central bank, even if at market interest rates, has real effects because it alleviates the interbank market friction and, as a result, it stimulates bank lending. We estimate the parameters of our extended Smets and Wouters (2003) model by matching impulse responses to the liquidity shock in the model and in the VAR. Consistently with the VAR evidence, the model's transmission mechanism goes through the impact of higher liquidity spreads on lending spreads. Also consistently with the VAR evidence, investment is the macroeconomic variable which is affected most heavily in quantitative terms; the responses of GDP, inflation and the policy rate are more muted.

Given the estimated parameters, we can use the structural model to investigate whether the liquidity shock can in fact account for a sizable share of the observed, large fall in aggregate investment in 2009–10. We focus on investment because it is the component of the national accounts which was most heavily affected by the crisis. According to our model, liquidity shocks alone account for over 30 percent of the fall in investment during the Great Recession.

We can also use the model to compute counterfactual no-policy scenarios, i.e. switch off the ECB's provision of liquidity in reaction to the interbank market tensions in order to assess its effectiveness. The results of this exercise suggest that the beneficial effects of the non-standard measures were substantial. In their absence, liquidity spreads would have been at least 200 basis points higher, lending spreads would have reached peaks of several percentage points, and their adverse impact on investment would have been more than twice as severe.

Our paper fits into the recent literature which evaluates the non-standard policy measures implemented by central banks during the Great Recession. Using structural VAR models, Peersman (2011) and Boeckx et al. (2017) capture non-standard measures by looking at the expansion of the ECB balance sheet and studying its implications. By affecting interest rate spreads of banks, the expansion of the balance sheet is effective in stabilizing the economy. Boeckx et al. (2017) further analyse how individual euro area countries were affected by these policies showing that the transmission was heterogenous among member states. Other studies based on reduced-form models assess the impact of the non-standard measures through conditional forecasts. Within a Bayesian VAR framework, Lenza et al. (2010) as well as Giannone et al. (2012) show that these policies had a significant effect in dampening the recession during the crisis. Compared to these studies, we analyse more specifically the impact of structural liquidity shocks and complement this analysis with a structural model that allows us to draw inference on the impact of liquidity shocks in the absence of non-standard monetary policy responses.

Fahr et al. (2013) as well as Cahn et al. (2017) also adopt a structural model to evaluate the impact of the ECB policies during the crisis. The former uses a counterfactual exercise to focus on the unlimited supply of liquidity to banks at a fixed rate (so-called fixed-rate-full-allotment) as well as the effect of the expansions of maturities at which liquidity was provided (so-called longer term refinancing operations with maturities of more than three month). Since Fahr et al. (2013) apply the framework by Christiano et al. (2010) their model does not explicitly include a characterisation of the interbank market. Similar to our paper, Cahn et al. (2017) use the framework by Gertler and Kiyotaki (2010) to better capture the bank lending channel of the non-standard measures. However, their paper does not focus on liquidity shocks, nor does it provide reduced-form (VAR) evidence on their impact.

Many other studies focus on the effects of the non-standard policy conducted in the US using a DSGE model. Amongst them, Gertler and Karadi (2013) show that this policy worked by replacing the private intermediation which broke down as financial markets froze up. Del Negro et al. (2017) attribute the effectiveness of the unconventional policies to the binding of the zero lower bound and the presence of nominal frictions. Christiano et al. (2015) conduct a counterfactual analysis focusing on how forward guidance dampened the effects of the recession.

The rest of the paper is organised as follows. Section 2 presents the VAR evidence on the impulse responses of the economy to a liquidity shock. Key features of our structural model are described in Section 3. Section 4 presents the estimation of selected structural parameters, based on the impulse response matching methodology. Our main results on the macroeconomic impact of the liquidity shock during the crisis and on the no-policy counterfactual are presented in Section 5. Section 6 draws some concluding remarks.

2 VAR evidence

In this section, we provide empirical evidence on the macroeconomic effects of interbank liquidity shocks. The financial crisis experience is crucially important in this respect. Under well-functioning and integrated financial markets, any bank liquidity needs should be quickly and efficiently satisfied by the interbank market. Liquidity shocks could therefore be expected to have no macroeconomic impact.[2] It is only when financial frictions become tight that liquidity shocks could be expected to produce real effects.

At the same time, it is clear that an increase in counterparty risk, for example due to variations in bankruptcy costs, or an increase in macroeconomic uncertainty, for example associated with a higher incidence of non-performing loans, could produce real effects irrespective of the tightness of interbank market frictions. If we wish to identify the real economy consequences of liquidity disruptions, a key step in our analysis must be the selection of a measure of spreads which only reflects interbank liquidity risk.

We start from interbank spreads, i.e., the spread between 3-month (uncollateralised) Euribor rates and the rate on 3-month overnight index swaps (OIS). The latter is a good proxy for risk-free rates, because the OIS contract does not require an exchange of the principal. The interbank spread is an indicator of money market stress, which increases when banks are less willing to lend to each other. However, the interbank spread is not only a proxy for liquidity risk. The increase in interbank spreads over the financial crisis went along with a generalised increase in overall uncertainty, which affected all measures of risk in financial markets, and a perceived increase in counterparty risk.

In the spirit of Bassett et al. (2014), we use regression analysis to identify the component of interbank spreads which is orthogonal to the contemporaneous increase in uncertainty and counterparty risk. Based on weekly data over the 2007-2014 sample,[3] we regress the interbank spread on the VSTOXX and banks' CDS spreads.

[2] The Global Financial Crisis of 2008-09 has led to an increase in attention towards macro-financial linkages, but the literature has mostly focused on the impact of a tightening of banks' credit supply conditions on economic activity–see e.g. Ciccarelli et al. (2015) and Bassett et al. (2014).

[3] The data is also available at the daily frequency, but does not overlap completely because the financial instruments are quoted in different markets that observe different holiday calendars. See appendix A for further details on the data set.

The former measure increases in overall uncertainty while the latter are direct measures of banks' counterparty risk. Moreover, we also add sovereign CDS spreads in the regression given that they can also be considered as proxies for banks' counterparty risk, because of the adverse feedback loop between euro area banks and sovereigns—see e.g. ECB (2014).

The results of this regression, reported in Table 1, confirm the high degree of comovement between the series. As a factor affecting the interbank spread, the VSTOXX variable is highly statistically significant but some CDS measures also prove to be significant. The $\overline{R}^2$ of the regression is 70%. We will use the residual of this regression as an indicator of liquidity spreads which is not contaminated by the effects of uncertainty shocks or the perceived increase in counterparty risk. This methodology leads to a conservative estimate of liquidity premia. The component of the interbank spread explained by the regression may also be partly associated with liquidity risk. If this were the case, the macroeconomic effectiveness of the ECB liquidity provision would be even stronger than shown by our model simulations.

Having derived a measure of liquidity spreads, we convert it to the quarterly frequency and include it in a VAR. The other time series in the VAR are real GDP, consumption, investment, inflation, the bank lending spread, the ECB policy rate, and the non-standard liquidity operation by the ECB. Bank lending spreads are measured as the difference between the interest rates on loans to non-financial corporations for up to one year and the 3-month OIS rate. We define the OIS rate as the ECB policy rate. The non-standard liquidity operations are defined as the sum of the two items on the ECB's balance sheet "lending to euro area credit institutions related to monetary policy operations" and "securities held for monetary policy purposes".[4] Both items are measured in terms of quarterly GDP.[5] We estimate the model over the available EMU sample, i.e. from 2001Q1 until 2014Q3.[6] The VAR includes one lag of all variables based on the Akaike and Schwarz information criteria.

We identify liquidity shocks in a recursive fashion using a Cholesky decomposition. This identification scheme faces the general challenge of disentangling the policy reactions to shocks in financial variables from financial variables' reactions to policy

[4] These operations exclude any liquidity injections carried out for lender of last resort reasons.

[5] See appendix A for further details on the data set.

[6] Our measure of liquidity spreads that we derived above ranges from 2007 to 2014. Since we assume that liquidity shocks did not occur prior to 2007, the liquidity spread is thus equal to the Euribor-OIS spread for the period 2001–2006.

shocks. In this paper, we deal with this problem by exploiting a property of the specific dataset we analyse. More specifically, VAR innovations in ECB liquidity provision and in liquidity spreads are essentially orthogonal to each other. The impact of identified liquidity shocks is therefore unchanged, irrespective of whether the ECB liquidity variable is ordered before or after the liquidity spread measure. In our benchmark results, we order central bank liquidity before the liquidity spread in the VAR, but we also show the results of the opposite ordering in appendix B.

Concerning the other variables, macroeconomic aggregates and inflation are always ordered first, while the other spreads and the short-term policy rate are allowed to react to liquidity shocks.[7] The key assumption in the Cholesky identification is therefore that the correlation between innovations to liquidity spreads R_{bt}/R_t and innovations to lending spreads R_{kt}/R_t is due to structural liquidity shocks. Conversely, this assumption implies that shocks to bank lending spreads do not have contemporaneous effects on liquidity spreads. This assumption seems to be intuitively appealing, given that our "pure" measure of liquidity risk R_{bt}/R_t should not be affected by changes in borrower riskiness, bankruptcy costs, etc., which would be natural candidates for exogenous variations in interbank spreads.

It should be noted that, even if the Cholesky decomposition does deliver a full set of orthogonal shocks, these shocks cannot easily be given a structural interpretation. Identifying other structural shocks is beyond the scope of this paper. We accordingly make no claims, for example, as to the empirical effects of the identified non-standard monetary policy shocks in the VAR.

Impulse responses to a liquidity shock are shown in shaded grey in Figure 2 together with 68% and 90% confidence bands.[8] The shock produces a short-lived annualised increase in liquidity spreads by 10 basis points. Bank lending spreads increase on impact by about 5 basis points and remain persistently at this higher level. Aggregate investment falls by almost 30 basis points on a quarterly rate. Consumption also tends to fall, but its reaction is quantitatively negligible. As a result, GDP decreases by about 10 basis points on a quarterly rate, which is a fraction of the investment response roughly consistent with the share of investment in GDP. Inflation and the policy rate also tend to fall, but only slightly. The liquidity shock is

[7]The ordering is as follows: GDP Y_t, consumption C_t, investment I_t, inflation P_t/P_{t-1}, non-standard liquidity measures M_t/Y_t, liquidity spread R_{bt}/R_t, bank lending spread R_{kt}/R_t, the ECB policy rate R_t.

[8]Confidence bands are based on a bootstrapped sample of 10,000 draws.

however met by a sizable increase in the amount of liquidity provided by the ECB.

One feature of our results is that the VAR is estimated over a sample including both tranquil times and the period of financial turmoil. It is conceivable that a structural break in macroeconomic dynamics occurred at the onset of the financial crisis. For robustness we therefore estimate the VAR also over the 2007Q1-2014Q3 period. Given the very sort sample size, we focus only on four variables: investment, ECB liquidity provisions, liquidity spreads and bank lending spreads. The results, shown in appendix B, are consistent with those of the VAR estimated over the longer sample.

To summarise, we document that a liquidity shock is met by an increase in the amount of central bank liquidity. Nevertheless, it leads to an increase in lending spreads and a reduction in economic activity, especially investment. The shock has small, possibly statistically insignificant effects on consumption and inflation. We will use the impulse responses to estimate some key parameters of our structural model, which is described in the next section.

3 The model

We rely on a general equilibrium model based on Smets and Wouters (2003) augmented with a banking sector as in Gertler and Kiyotaki (2010). The banking sector is composed of a retail and a wholesale market. The former market allows banks to raise deposits from households, while the latter is an interbank market where banks provide funding to each other. Both markets are characterised by an agency problem à la Gertler and Karadi (2011). Bankers can divert a fraction of the bank assets financed by either retail or wholesale deposits. These frictions give rise to spreads between the return on capital, the interbank rate and the risk-free rate. In addition, we introduce the possibility of a liquidity provision to banks by the central bank. The key difference between our model and Gertler and Kiyotaki's (2010) is that we allow for the frictions on the wholesale market to be time-varying in a stochastic fashion.

Banks invest in non-financial firms that differ in their opportunities to issue debt. In each period a given fraction of firms can issue new assets while the remaining fraction merely rolls over its existing debt. The opportunity to issue new assets arrives randomly to firms, but before the realization is known, firms and banks already engage in a business relationship. We make this assumption for two reasons. First, such a framework is supposed to reflect the relationship-based financial system that predominates in Europe. Second, it creates the necessity of an interbank market. After the realization of investment opportunities, banks are either in short or abundant supply of liquidity depending on their business relationship with firms. This liquidity is traded in the interbank market. In what follows, we only discuss the main structure of the model and describe all frictions in the economy.[9]

3.1 Households

Each household consists of a given fraction of workers and bankers. Workers supply labour to the production sector while bankers manage financial intermediaries. Both agents transfer their earnings to their household and perfectly pool their consumption risk. Each period a banker switches occupation with a probability of $1-\sigma$ and becomes a worker instead. The probability to switch occupation is independent of the duration agents have been bankers. Exiting bankers transfer the net worth they have accumulated during their term in office to their household. All exiting bankers are randomly replaced by workers, who will then become bankers. These new bankers obtain start-up capital from their household. While bankers are the owners of the bank they manage, it is assumed that households place their deposits in banks belonging to other households. This assumption is needed to motivate the moral hazard problem that will be introduced in subsection 3.3. Each household j consumes a non-durable consumption good C_{jt}, provides labour to firms L_{jt}, for which it earns the real wage W_{jt}, and holds deposits D_{jt}, which pay the real deposit interest rate R_t. Households maximize the following utility function:

$$E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\log\left(C_{jt} - hC_{jt-1}\right) - \frac{\left(L_{jt}\right)^{1+\varphi}}{1+\varphi} \right] \right\}, \tag{1}$$

where β stands for the discount factor, $h \in (0,1)$ measures the influence of past consumption on utility and φ denotes the inverse elasticity of labour supply. The budget constraint is given by:

$$C_{jt} + D_{jt} + T_{jt} = R_{t-1}D_{jt-1} + W_{jt}L_{jt} + \Pi_{jt}, \tag{2}$$

[9] A technical appendix that goes through all of the derivations in much more detail is available upon request.

with Π_t being profits from firms as well as transfers from exiting bankers net the start-up capital granted to new bankers. Finally, households pay lump-sum taxes T_{jt} to finance any government expenditures.

Following Smets and Wouters (2003) wages are assumed to be sticky. Households are monopolistic suppliers of differentiated labour services. Each household provides labour to intermediate goods producers for which they receive a household-specific wage W_{jt}. The aggregate labour demand by these firms is given by the following Dixit-Stiglitz type aggregator function:

$$L_t = \left[\int_0^1 (L_{jt})^{\frac{\varepsilon_l - 1}{\varepsilon_l}} \, dj \right]^{\frac{\varepsilon_l}{\varepsilon_l - 1}} ,$$

where ε_l controls the elasticity of substitution among different types of labour. Each period only a fraction $1-\theta_w$ of wages can be re-negotiated. When negotiating wages, households maximize their utility (1) subject to their budget constraint (2) and to the firms' demand schedule for L_{jt}. For the remaining fractions θ_w of wages, which are not re-negotiated in the current period, we assume that these wages are indexed to past inflation and are mechanically adjusted according to the CPI inflation of the previous period. This indexation is however only partial, with $\chi_w \in (0, 1)$ controlling the intensity of the wage indexation.

3.2 Firms, technology, and nominal rigidities

We have four types of firms operating in the production sector. Intermediate goods producers combine labour and capital to produce intermediate goods which they sell to retailers. Retailers differentiate these goods and sell them to the final goods producers. In the final goods sector retail goods are combined to consumption goods, which are then consumed by households. While intermediate and final goods producers operate under perfect competition and are able to adjust prices every period, there is monopolistic competition and staggered price setting à la Calvo (1983) in the retail sector. Capital goods are constructed by capital goods producers using consumption goods as sole input. Creating capital is subject to flow adjustment costs.

3.2.1 Intermediate goods producers

Intermediate goods producers fulfill two tasks in this economy. They produce an intermediate good $Y_t^{\mathcal{M}}$, which will be the sole input for producing the final good Y_t, and they sell assets to banks in order to finance the capital stock K_t used in production. Intermediate firms differ in their investment opportunities and we differentiate between two types of firms. Each period a fraction γ^i of firms receives a signal allowing them to acquire new capital. The remaining fraction $\gamma^n = 1 - \gamma^i$ of intermediate goods producers cannot change their capital stock. The signal to firms is assumed to be *iid* across time. We will use the superscript $h = \{i, n\}$ to differentiate between investing and non-investing firms. All intermediate goods producers face an identical constant-returns-to-scale production function and we assume that labour is perfectly mobile across these firms. Therefore, we do not need to keep track of the distribution of capital across intermediate goods producers. Aggregate intermediate output $Y_t^{\mathcal{M}}$ can be expressed as a function of aggregate labour L_t and aggregate capital K_t:

$$Y_t^{\mathcal{M}} = K_t^{\alpha} L_t^{(1-\alpha)}, \qquad (3)$$

with α being the share of capital in the production function. The law of motion for the capital stock is given by the sum of newly acquired capital I_t by investing firms, the depreciated capital stock $\gamma^i (1-\delta) K_t$ of these firms, and the depreciated capital stock $\gamma^n (1-\delta) K_t$ of non-investing firms in the current period:

$$\begin{aligned} K_{t+1} &= I_t + \gamma^i (1-\delta) K_t + \gamma^n (1-\delta) K_t \\ &= I_t + (1-\delta) K_t. \end{aligned}$$

The parameter δ is the depreciation rate which is assumed to be identical for both types of firms.

Intermediate goods producers completely finance their capital acquisitions in advance by issuing assets. They sell these assets to the bank with which they have built up a business relationship at the beginning of each period. In contrast to banks, intermediate goods producers face no constraints on obtaining funding. They use the capital stock as collateral so that the issued assets are claims against capital. Since we assume no frictions in originating these assets, the asset price is equal to the price of one unit of capital. Following Gertler and Kiyotaki (2010) we conjecture that asset prices differ between the two types of firms. Let S_t^h be the claims issued by a firm of type h and Q_t^h the asset price of these claims (in real terms). The value of originated claims is then equal to the value of capital:

$$\begin{aligned} Q_t^i S_t^i &= Q_t^i \left[I_t + \gamma^i (1-\delta) K_t \right], \\ Q_t^n S_t^n &= Q_t^n \gamma^n (1-\delta) K_t. \end{aligned}$$

Since financing the capital stock is frictionless and intermediate goods producers issue perfectly contingent claims against their capital, these assets can either be interpreted as equity or perfectly state-dependent debt. Intermediate goods producers operate under perfect competition and earn zero profits. Each period they sell their products to retailers at a real price of $P_t^{\mathcal{M}}$ and pay workers a wage W_t. The latter is an aggregate of the individuals wages W_{jt}. The gross profit per unit of capital can thus be expressed as:

$$Z_t = \frac{P_t^{\mathcal{M}} Y_t^{\mathcal{M}} - W_t L_t}{K_t},$$

which will be collected by banks. For banks the gross rate of return on assets is then given by the dividend Z_t they collect as well as the price development of assets. Since the price depends on the type of firm, we define the return (in real terms) between period $t-1$ and t as:

$$R_{kt}^{hh'} = \frac{Z_t + (1-\delta) Q_t^{h'}}{Q_{t-1}^h},$$

with h being the type of firm at time $t-1$ and h' being the type of firm at time t. Since the capital stock depreciates at the rate of δ between periods, the value at time t is given by $(1-\delta) Q_t^{h'}$.

3.2.2 Retailers

Retailers merely repackage intermediate goods. They do this at no cost and one unit of intermediate goods can be transferred into one unit of retail goods. In doing so, they differentiate these goods and since retailers operate under monopolistic competition, each retailer i adds a mark-up to the marginal costs (given by the price of intermediate goods $P_t^{\mathcal{M}}$). Retailers then sell their goods $Y_{it}^{\mathcal{R}}$ at a price P_{it}. Retail prices are assumed to be sticky with $1-\theta_p$ being the probability that retailers can readjust prices in the current period. We also assume price indexation to past inflation so that the fraction θ_p of retailers, who do not adjust their prices in the current period, mechanically change their price according to the inflation of the previous period. Retailers solve the following optimization problem:

$$\max_{P_{it}} E_t \sum_{s=0}^{\infty} \theta^s \Lambda_{t,t+s} \left\{ \left[\prod_{\tau=1}^{s} \left(\frac{P_{t+\tau-1}}{P_{t+\tau-2}} \right)^{\chi_p} \frac{P_{it}}{P_{t+s}} - P^{\mathcal{M}}_{t+s} \right] Y^{\mathcal{R}}_{it+s} \right\}, \tag{4}$$

subject to future demand by final goods producers (6). The parameter $\chi_p \in (0,1)$ controls the intensity of the price indexation, while $\Lambda_{t,t+s}$ is the stochastic discount factor derived from Euler equation of households. Profits earned by retailers are rebated lump sum back to households.

3.2.3 Final goods producers

Final goods producers aggregate the differentiated goods $Y^{\mathcal{R}}_{it}$ they buy from retailers according to the following Dixit-Stiglitz type aggregator function:

$$Y_t = \left[\int_0^1 Y_{it}^{\mathcal{R}\,\frac{\varepsilon_y - 1}{\varepsilon_y}} \, di \right]^{\frac{\varepsilon_y}{\varepsilon_y - 1}}, \tag{5}$$

with ε_y being the price elasticity of retail goods. The final good Y_t is then either sold to households or used as input factor in the production of capital goods. The cost minimization of final goods producers leads to the demand function for retail goods:

$$Y^{\mathcal{R}}_{it} = \left(\frac{P_{it}}{P_t} \right)^{-\varepsilon_y} Y_t. \tag{6}$$

The price P_t is an aggregate of retail prices:

$$P_t = \left[\int_0^1 (P_{it})^{1-\varepsilon_y} \, di \right]^{\frac{1}{1-\varepsilon_y}}, \tag{7}$$

and can be interpreted as the CPI index.

3.2.4 Capital goods producers

Capital goods producers provide new capital to the intermediate goods producers that received a signal allowing them to acquire new capital. They sell the new capital to these firms at the market price of Q^i_t. Creating capital is subject to flow adjustment costs so that capital goods producers solve the following profit maximization problem:

$$\max_{I_t} E_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \left[(Q_s^i - 1) I_s - F\left(\frac{I_s}{I_{s-1}}\right) I_s \right]. \tag{8}$$

As in Christiano, Eichenbaum and Evans (2005) the cost function $F(\cdot)$ is convex ($F''(\cdot) > 0$) and adjustment costs are zero in the steady state ($F(1) = F'(1) = 0$). Due to the adjustment costs, capital goods producers earn profits outside of the steady state. These are rebated lump sum back to households.

3.3 Banks

Banks channel funds from households to the production sector. They finance themselves through deposits collected from households and through retained earnings that they use to build up equity. Additionally, banks interact on an interbank market which allows those that are short of liquidity to borrow from those having abundant liquidity. We introduce the necessity of an interbank market by assuming the following timing: At the beginning of each period, banks and intermediate goods producers engage in a business relationship before these firms receive a signal on their ability to issue new assets. Based on the expected liquidity needs banks collect deposits from households. After this retail market has closed, firms receive a signal and either issue new assets or merely roll over their existing debt. Therefore, banks are either in short or abundant supply of liquidity. Since the interbank market opens after firms and banks know about their investment opportunities, this market allows banks to manage their short-term liquidity needs. The collection of deposits in this model should thus be understood as longer-term financing. In addition to the aforementioned funding alternatives, we introduce the possibility of a liquidity provision by the central bank, which we will later interpret as the non-standard policy tools used by the ECB after 2007.

Besides creating the necessity of an interbank market, the assumption of banks and firms engaging in a business relationship before they have knowledge of their investment opportunities shall represent a banking-based financial system. In contrast to the US, the financing of firms heavily depends on banks in the euro area. At the beginning of each period, banks choose the intermediate goods producers they want to finance. At the end of the period, claims to the intermediate goods producers are pooled across banks. As a result, ex-ante expected returns are equalized across banks at the beginning of each period. This simplification is useful to avoid keeping track of the distribution of net worth across banks.

According to the aforementioned timing, bank j first decides on the amount of deposits D_{jt} it borrows from households based on its expected investment opportunities. Next, after learning about its investment opportunities, bank j decides on the amount of firms' assets S^h_{jt} it buys for a given price Q^h_t, on the amount of interbank borrowing B^h_{jt} (a negative value indicates that bank j offers liquidity on the interbank market) and possibly on the amount of liquidity M^h_{jt} it borrows from the central bank. The superscript $h = \{i, n\}$ indicates whether the bank finances an investing firm ($h = i$), or a non-investing firm that merely rolls over its debt ($h = n$). Notice that due to our assumption on the timing, the amount of deposits D_{jt} is independent of the bank type, while everything else depends on the type indicated by the superscript h. The balance sheet of bank j thus reads:

$$Q^h_t S^h_{jt} = N^h_{jt} + D_{jt} + B^h_{jt} + M^h_{jt},$$

with N^h_{jt} denoting the amount of net worth of bank j. Net worth is accumulated over time as the difference between earnings on assets and debt payments:

$$N^h_{jt} = \left[Z_t + (1-\delta)\, Q^h_t\right] S_{jt-1} - R_{t-1} D_{jt-1} - R_{bt-1} B_{jt-1} - R_{mt-1} M_{jt-1},$$

where R_t, R_{bt}, and R_{mt} denote the real gross interest rates paid on deposits, interbank loans, and loans provided by the central bank, respectively. The gross returns on assets $\left[Z_t + (1-\delta)\, Q^h_t\right]$ do not only include the dividend payment Z_t from intermediate goods producers, but also the resale value of assets $(1-\delta)\, Q^h_t$, which depends on the type of bank. Due to financial frictions, which will be introduced below, banks can expect a premium between the return on assets and the interest payments on liabilities. Such a premium gives bankers an incentive to accumulate assets over time and to maximize the value of the bank. Since bankers have to exit the market at the end of each period with probability $1-\sigma$, the value of bank j measured at the end of the period (but measured before banks pool their claims to intermediate firms) is given by its expected terminal wealth:

$$V_{jt} = E_t \sum_{i=1}^{\infty} (1-\sigma)\, \sigma^{i-1} \Lambda_{t,t+i} N^h_{jt+i},$$

with $\Lambda_{t,t+i}$ being again the stochastic discount factor derived from the Euler equation of households.

Financial frictions are modeled as in Gertler and Karadi (2011). We assume an agency problem between banks and their creditors as banks can divert a certain fraction of assets and transfer them to the household they belong to. When a banker diverts funds, the bank will be closed and the remaining fraction of assets serves as bankruptcy assets that is distributed among creditors, i.e. depositors, the central bank as well as those banks holding interbank market claims against the defaulting bank. As in Gertler and Kiyotaki (2010), we assume that the degree of financial frictions differs among the two funding markets. Banks can divert assets financed by borrowing from households more easily than those financed by borrowing from other banks or the central bank. The way financial frictions are introduced results in an endogenous constraint on bank's ability to obtain funding. Creditors are only willing to provide funding to a bank as long as the banker has no incentive to divert assets. To ensure this, the value of the bank V_{jt} needs to exceed the gain a banker receives by diverting assets:

$$V_{jt} \geq \theta \left(Q_t^h S_{jt}^h - \omega_t B_{jt}^h - \omega_m M_{jt}^h \right). \tag{9}$$

According to this incentive constraint the value of the bank V_{jt} must exceed the fraction θ of assets which a banker can divert. As in Gertler and Kiyotaki (2010), ω_t and ω_m (with $\omega_t, \omega_m \in (0,1)$) measure the possibility of diverting funds financed by interbank borrowing B_{jt}^h and by borrowing from the central bank M_{jt}^h, respectively. With $\omega_t = 1$ or $\omega_m = 1$, banks cannot divert assets financed by interbank borrowing or the liquidity provision by the central bank. With $\omega_t < 1$ or $\omega_m < 1$, the respective creditors would lose $(1-\omega_t)\, B_{jt}^h$ and $(1-\omega_m)\, M_{jt}^h$ in a bankruptcy.

While ω_m will be constant, we depart from Gertler and Kiyotaki (2010) and assume ω_t to be time-varying, following an AR(1) process in logs:

$$\log(\omega_t) = (1-\rho_\omega)\,\bar{\omega} + \rho_\omega \log(\omega_{t-1}) + e_{\omega,t}, \tag{10}$$

with $\bar{\omega}$ being the steady state of the shock and $e_{\omega,t}$ denoting the structural innovation to the shock. The variable ω_t can be interpreted as a liquidity shock, which indexes the willingness of banks to lend in the interbank market. In the policy exercise conducted in Section 4 we will use a fall in ω_t to simulate the freezing up of the interbank market observed during the financial crisis in the euro area.

Every period, the fraction $1-\sigma$ of bankers leaving the market is replaced by new bankers. This assumption is introduced to prevent the net worth of banks to increase indefinitely. If bankers did not leave the market, they could accumulate enough equity to ensure that the incentive constraint (9) is never binding. When leaving the market, bankers transfer their net worth to their respective household. New bankers obtain start-up capital from their households proportional to the asset holdings of an exiting bank. We define aggregate net worth N_t^h for banks of type h as the sum of net worth of existing (old) banks N_{ot}^h and of new (young) banks entering the market N_{yt}^h:

$$N_t^h = N_{ot}^h + N_{yt}^h.$$

Net worth of existing banks is given by the difference of earnings from holding assets and interest payments on liabilities. As the mass of existing banks is σ and the mass of banks from type h is γ^h, aggregate net worth of existing banks is given by:

$$N_{ot}^h = \sigma\gamma^h \left\{ \left[Z_t + (1-\delta)\, Q_t^h\right] S_{t-1} - R_{t-1}D_{t-1} - R_{mt-1}M_{t-1} \right\},$$

where we have dropped the j subscript to denote aggregate bank variables. We assume that entering banks obtain a fraction $\xi/(1-\sigma)$ of the asset holdings of an exiting bank. Net worth of new banks is then given by:

$$N_{yt}^h = \xi\gamma^h \left[Z_t + (1-\delta)\, Q_t^h\right] S_{t-1}.$$

Notice that due to the aggregation interbank loans cancel out in both definitions. Finally, the aggregate balance sheet for the entire banking sector obeys:

$$Q_t^i S_t^i + Q_t^n S_t^n = N_t^i + N_t^n + D_t + M_t.$$

3.4 Closing the model

To close the model we impose market-clearing conditions for all markets. Furthermore, we define policy rules for the conventional monetary policy as well as the non-standard measures.

3.4.1 Market clearing

In the financial market, the labour market, the intermediate goods sector, the retail goods sector as well as the capital goods sector supply has to be equal to demand. The government budget constraint requires that the non-distortionary lump-sum taxes collected from households are used to finance the central bank liquidity injections. In the final goods sector output is equal to the demand of households, the demand for investment goods from capital producers, and the investment adjustment costs:

$$Y_t = C_t + I_t + F\left(\frac{I_t}{I_{t-1}}\right) I_t. \tag{11}$$

3.4.2 Central bank policies and interest rates

Monetary policy is conducted by the central bank with an interest rate rule that targets CPI inflation and real output growth. Following Smets and Wouters (2003), we introduce a Taylor-type rule prescribing that the nominal policy rate $R_t^{\mathcal{N}}$ reacts to the lagged interest rate, inflation, the growth rate of inflation, the output gap (which we proxy as deviation of real output from its steady state) as well as the growth rate of the output gap:

$$\frac{R_t^{\mathcal{N}}}{R^{\mathcal{N}}} = \left(\frac{R_{t-1}^{\mathcal{N}}}{R^{\mathcal{N}}}\right)^{1-\gamma_R} \left[\left(\frac{P_t}{P_{t-1}}\right)^{\gamma_\pi} \left(\frac{P_t}{P_{t-1}} / \frac{P_{t-1}}{P_{t-2}}\right)^{\gamma_{\Delta\pi}} \left(\frac{Y_t}{Y}\right)^{\gamma_Y} \left(\frac{Y_t}{Y} / \frac{Y_{t-1}}{Y}\right)^{\gamma_{\Delta Y}}\right]^{\gamma_R}. \tag{12}$$

The relationship between the nominal and the real risk-free interest rate is given by the Fisher equation:

$$R_t^{\mathcal{N}} = R_t E_t \frac{P_{t+1}}{P_t}.$$

A monetary policy rule as in equation (12) is standard in the literature and known to describe well actual policy interest rate levels over the decades before the Global Financial Crisis. For our model, we also need to specify a rule followed by the central bank for injecting liquidity in the market. Given the unprecedented nature of these non-standard monetary policy measures, we cannot rely on existing results in the literature. It is hard to capture the different types of non-standard measures adopted by the ECB over the crisis years through a unique non-standard "monetary policy instrument". One may argue that the actual non-standard monetary policy instrument was the interest rate on ECB loans to banks, R_{mt}, because the quantity of liquidity provided by the ECB was by and large demand-driven at the rate of the main refinancing operations (MRO). However, the actual interest rate on ECB liquidity was larger than the MRO, since such loans were conditional on the provision of adequate collateral. We therefore specify the non-standard policy rule in terms of the quantity of liquidity provided by the ECB. The resulting interest rate R_{mt} will give us a model-implied valuation of the total cost of ECB liquidity–given by the sum of the actual MRO rate and the opportunity cost of the pledged collateral.

We assume that liquidity injections M_t relative to GDP were related to the liquidity spread:

$$\log\left(\frac{M_t}{Y_t}\right) = \rho_M \log\left(\frac{M_{t-1}}{Y_{t-1}}\right) + \gamma_{R^b} \log\left(\frac{R_{bt}}{R_t} / \frac{R_b}{R}\right). \tag{13}$$

An important feature of this policy rule is that it assumes that all agents in the economy anticipate the ECB intervention given the widening of liquidity spreads. Furthermore, equation (13) also assumes that liquidity injections are persistent, so that they would be withdrawn slowly in the face of a narrowing of spreads.

4 Parameter estimation

We are interested in understanding the dynamics of key macroeconomic variables following a liquidity shock. Therefore, we estimate our model using the strategy in Christiano et al. (2011) that minimizes the distance between the dynamic response to shocks in the model and in the structural VAR. In this section we describe the calibration of model parameters and present the impulse response matching strategy together with the estimation results.

4.1 Calibration

Model parameters, which cannot be identified by our impulse response matching strategy, are calibrated. For calibrating the parameters associated with the real economy we mainly follow Smets and Wouters (2003). Parameter values for the financial sector are taken from Gertler and Kiyotaki (2010). The calibration is summarized in Table 2. We set the discount factor of households to $\beta = 0.99$, which implies an annual risk-free interest rate of 4 percent. The capital share in production is equal to $\alpha = 0.3$ and we set the depreciation rate to $\delta = 0.025$, assuming an annualized depreciation rate of 10 percent. Smets and Wouters (2003) estimate for the euro area a habit formation parameter of $h = 0.592$ and an inverse Frisch elasticity of labour supply of $\varphi = 2.503$.[10] Furthermore, they estimate the probability of being able to adjust prices and wages to be equal to $(1-\theta_p) = 0.095$ and $(1-\theta_w) = 0.258$, respectively. The indexation of prices and wages is equal to $\chi_p = 0.477$ and $\chi_w = 0.728$, respectively. We set the elasticity of substitution between retail goods to $\varepsilon_y = 10$ and between labour to $\varepsilon_l = 3$. This implies a price mark-up of 10 percent and a wage mark-up of 50 percent.

Following Gertler and Kiyotaki (2010) we assume that on average bankers are in office for 10 years ($\sigma = (40-1)/40$). The transfer to entering bankers ξ as well as the fraction of divertable assets θ are calibrated to allow for an average leverage ratio of 4 and an average annualized spread between the return to capital R_{kt}^{ii} and the risk-free interest rate R_t of 100 basis points. We assume that in the steady state interbank market frictions are negligible and calibrate the average degree of interbank market frictions to $\bar{\omega} = 0.99$. Setting this parameter not equal to unity has practical reasons. As shown by Gertler and Kiyotaki (2010) with frictionless interbank markets ($\omega_t = 1$) the model simplifies to the framework of Gertler and Karadi (2011), making the differentiation between banks irrelevant. In such a setting, all banks are balance sheet constrained. However, under our calibration, with imperfect interbank markets ($\omega_t < 1$) only banks which have the opportunity to invest in new assets are constrained. Banks which have no investment opportunities in the current period are not balance sheet constrained. They have sufficient funds relative to their lending opportunities and are therefore willing to provide liquidity to other banks in the interbank market. For this reason, we do not allow the degree of interbank market frictions ω_t to increase to 1 in our exercise. In order to make banks in steady state indifferent between interbank loans and liquidity provided by the central bank we set $\omega_m = \bar{\omega}$. Finally, Smets and Wouters (2003) estimate the inflation coefficient and the inflation growth coefficient in the Taylor rule to be $\gamma_\pi = 1.688$ and $\gamma_{\Delta\pi} = 0.151$, respectively. The coefficients for the output gap and the growth in the output gap are $\gamma_y = 0.098$ and $\gamma_{\Delta y} = 0.158$, respectively. The inertia parameter is $\gamma_R = 0.956$.

[10] In contrast to our model, Smets and Wouters (2003) use external instead of internal habit formation.

4.2 Impulse response matching

The most relevant model parameters for the transmission of a liquidity shock ω_t to the real economy are estimated. We do so by matching four impulse responses identified in the VAR with the corresponding dynamic responses of the structural model. More specifically, we rely on the Bayesian version of this methodology proposed in Christiano et al. (2011).

We will briefly summarise the methodology before presenting the estimation results and the matched impulse responses. Let $\hat{\Psi}$ be a vector in which we stack the estimated impulse responses and $\Psi(\Theta)$ be an analogous vector of the model-implied responses depending on the model parameters Θ. According to large sample theory and given the (unknown) true values of these model parameters Θ_0, we can express the asymptotic distribution of the estimated impulses as:

$$\hat{\Psi} \sim N\left(\Psi\left(\Theta_0\right), V\right).$$

Christiano et al. (2011) show how to compute the likelihood of the data $\hat{\Psi}$ as a function of the model parameters Θ and the covariance matrix V. To do so, we need a consistent estimator of the matrix V. Following the authors, we use a bootstrap approach and compute

$$\bar{V} = \frac{1}{T}\sum_{i=1}^{T}\left(\Psi_i - \bar{\Psi}\right)\left(\Psi_i - \bar{\Psi}\right)',$$

with Ψ_i being the ith realization of the impulse responses obtained by the bootstrapping procedure and $\bar{\Psi}$ being the mean realization. We set $T = 10.000$. Finally, our estimator for the covariance matrix V includes only the diagonal elements of $\bar{V}$.[11] Given the likelihood function and the priors on the model parameters Θ, we can then use the standard steps in Bayesian estimation to obtain the posterior distribution of Θ.

We summarize the priors and posteriors for the estimated parameters in Table 3. The posterior distributions are obtained by the Metropolis-Hasting algorithm with 250.000 draws. We opt for a standard Beta prior centered at 0.75 for the persistence of the liquidity shock ρ_ω as well as the persistence parameter in the policy function

[11] Christiano et al. (2011) discuss possible transformations of the matrix $\bar{V}$, which can be used to assign different weights to impulse responses in the estimation. For transparency reasons, they finally stick to $\bar{V}$ and also use its diagonal elements.

ρ_M. The prior mean for the coefficient in the policy function γ_{R_b} as well as the fraction of firms without investment opportunities γ^n is taken from the calibration used in Gertler and Kiyotaki (2010). To let the data speak, we choose prior standard deviations for these two parameters which correspond to fairly loose priors. This means that with 95 percent probability the coefficient in the policy function γ_{R_b} lies between 60 and 140 while the fraction of firms without investment opportunities γ^n lies between 53 percent and 92 percent. The posterior mean for the coefficient of the policy function indicates that an annualized increase in the liquidity spread by 100 basis points leads to a mean liquidity provision of 23 percent (relative to quarterly GDP) by the ECB. Our posterior mean of 82 percent for the fraction of firms without investment opportunities is a little bit higher than the calibrated value by Gertler and Kiyotaki (2010). We opt for a rather low prior mean for the inverse of the elasticity of net investment to the price of capital η, because financial frictions in our model already restrain producers in their ability to invest. The posterior mean of 1.24 is slightly lower than the calibrated value used by Gertler and Kiyotaki (2010). The standard deviation of the liquidity shock is estimated to be 0.03.

We tried to include other parameters in the estimation, especially parameters related to the financial sector like the economy-wide leverage ratio or the survival rate of bankers. Since these parameters do not seem to affect the dynamic responses significantly, we rather keep them at their standard calibrated values.

Figure 2 shows the impulse responses of the VAR together with the matched responses by the model. The model does very well at capturing the responses of the liquidity spread R_{bt}/R_t, the bank lending spread R_{kt}/R_t as well as the liquidity provision M_t/Y_t to banks by the central bank.[12] It does a reasonable job at accounting for the transmission of an impaired interbank market to the real economy by matching a sizable fraction of the drop in investment I_t. The model can match to a lesser extent the dynamics of consumption C_t, of GDP Y_t, of the short-term interest rate R_t and of inflation P_t/P_{t-1}. Nevertheless the model's responses are all within the VAR confidence bands.

In the next section we will use the model to provide a quantitative assessment of the macroeconomic impact of the ECB's non-standard measures.

[12] Our model implied lending rate R_{kt} reported in the impulse responses is a weighted average of the gross return on assets $R_{kt}^{hh'}$.

5 The financial crisis in the euro area

In this section, we study the financial crisis and its macroeconomic consequences through the lens of our model. We begin by looking again at the impulse responses of a one standard deviation liquidity shock and compare the model impulse responses with the counterfactual case of absence of ECB's non-standard intervention. For this purpose, we set to zero all monetary injections implied by the policy rule (13). To understand the mechanism at work behind the non-standard policy rule, we also study the case in which the monetary policy intervention is unexpected, i.e. akin to a liquidity supply shock. Finally, we simulate the path of the interbank market shock ω_t which replicates the surge in the liquidity spread over the 2007-2012 period. Given this path, we can compute its effect on all endogenous variables and compare them with their empirical counterparts to evaluate how much of the Great Recession is due to the interbank market tensions which we have identified with our model. Moreover, we can compute a counterfactual scenario for the period 2007-2012.

5.1 The effects of the liquidity shock—a counterfactual analysis

To assess the effects of the ECB's non-standard measures, Figure 3 depicts the impulse responses of a one standard deviation liquidity shock ω_t (solid line) and compares them with the effects of such a shock in the absence of the liquidity injections (dashed line). Thus, in the counterfactual analysis, the liquidity injection by the central bank is no longer described by the policy function (13), but we set $M_t = 0$.

The comparison of the benchmark model with the counterfactual analysis shows that the provision of liquidity to the financial sector helps to dampen the effect of ω_t on spreads and via this on the real economy. Without the intervention, the surge on impact of the liquidity spread R_{bt}/R_t as well as the bank lending spread R_{kt}/R_t is larger by a factor of three. Furthermore, the effect of ω_t does not die off as quickly as it does when the central bank intervenes. With the liquidity injections, the tensions in the interbank market—measured by the liquidity spread R_{bt}/R_t—already disappear after two quarters. In contrast, the tensions will last for two years, if we set $M_t = 0$. Similar effects hold for the credit conditions for the non-financial sector R_{kt}/R_t, although the non-standard policy is not able to bring down rates as quickly as in the interbank market. This has consequences for the real economy. Without the non-standard policy the maximal decline in investment is three times as large.[13]

An impairment of the interbank market (i.e. a reduction in ω_t) tightens the incentive constraint (9) and without the central bank intervention banks are forced to reduce their lending for any given level of net worth. As a consequence, interest rate spreads increase and investment declines. By substituting interbank lending with central bank lending, policy makers can directly affect the incentive constraint. A one-to-one substitution of interbank borrowing B^i_{jt} by central bank liquidity injections M^i_{jt} decreases the incentive constraint by $\theta\left(\omega_m - \omega_t\right)$. In our framework, the central bank can therefore even lend at a higher rate than the interbank market rate ($R_{mt} > R_{bt}$) during a financial crisis.[14]

In summary, the liquidity provision under the non-standard policy serves as a powerful tool to counteract tensions in the interbank market and to attenuate the spillovers to the real economy. In the next section, we will look in more detail at how the non-standard policy in our model acts on the economy.

5.2 Understanding the non-standard policy rule

The counterfactual analysis in the previous section suggests that the liquidity injection by the ECB had a large effect on spreads and investment. To better understand this effect, this section compares it to that of a surprise central bank liquidity injection. The difference between the two responses is informative of whether liquidity injections are especially powerful when they are the predictable response to exogenous financial shocks.

We therefore add an innovation to the non-standard policy function (13) and normalize this surprise liquidity injection in period $t = 0$ to be equal to the response of the non-standard policy to a one standard deviation liquidity shock. The impulse responses of such a non-standard policy shock are shown in Figure 4. The surprise injection lets spreads decrease by 60 basis points, while the improvement

[13] Under both scenarios, the model-implied responses of consumption, inflation as well as the short-term rate are economically insignificant and we therefore refrain from reporting them.

[14] Note that for B^i_{jt} and M^i_{jt} we use the superscript i, since in equilibrium only banks with investment opportunities in the current period borrow on the interbank market and are willing to accept liquidity provided by the central bank.

in investment is merely 0.1 percent. As the magnitude of the liquidity injection due to the non-standard policy shock is equal to the rule-based injection in response to the liquidity shock ω_t (and since we linearise our model), we can directly compare the two effects. The comparison with the counterfactual analysis of Figure 3 reveals that the effects of non-standard policy are much smaller, when they occur as an exogenous shock, rather than in an anticipated reaction to a liquidity disruption.

One key reason is that the effects of liquidity injections depend on financial market conditions. When the interbank market is not impaired (and $\omega_t = \omega_m$), the central bank has no advantage over private lending and central bank liquidity is merely a substitute for interbank lending ($\theta\left(\omega_m - \omega_t\right) = 0$). A liquidity injection therefore produces negligible benefits. It is only when interbank markets become impaired (and $\omega_t < \omega_m$) that the central bank gains a clear advantage over private lenders. The effects of central bank liquidity are then magnified.

Another way to understand the small accommodative effect shown in Figure 4 is through the influence of the liquidity injection on assets prices. As a result of central bank liquidity injections, asset prices rise and loosen the incentive constraint (9), so that banks are able to provide more credit to the non-financial sector. The non-standard policy rule (13) is thus a powerful tool during crisis periods. It has only minor effects during normal times.

5.3 Accounting for the financial crisis

Up to now we have only looked at a one standard deviation of the interbank market shock. During the financial crisis the economy was arguably hit by a sequence of these shocks that caused a longer lasting impairment of the interbank market. In this section, we simulate the impairment of the euro area interbank market for the period 2007–2012. This allows us to evaluate how much of the Great Recession is due to the interbank market tensions that we have identified with our model. Furthermore, it allows us to make a statement regarding the total effect of the impaired interbank market on the economy. In a second step, we will again conduct a counterfactual analysis to assess the total effect of the ECB's non-standard measures.

To simulate the impairment of the interbank market, we determine the path of the liquidity shock ω_t which replicates the surge in the liquidity spread R_{bt}/R_t during 2007-2012. Taking the reduced form first order state-space representation of our model, we can extract a series of innovations to ω_t which are needed to match the path of R_{bt}/R_t. Knowing this path, we can then compute the effects of the liquidity shock on all endogenous variables and compare them with their empirical counterparts.

This part of our analysis is based on several assumptions. First, we need to assume that in 2007 we start in the steady state of the model and that after the controlled period (i.e. after 2012) agents expect all variables to return to their steady state. This implies that agents know that any disturbances in the interbank market are only temporary. Second, while agents expect the central bank to intervene as soon as the economy is hit by a liquidity shock according to its non-standard policy rule (13), the innovations to ω_t, which we back out in this exercise, are unforeseen by all agents in every period. They only know how these innovations decay given the definition of the shock (10).

The solid lines in Figure 5 show the impact of the liquidity shock ω_t over the period 2007Q2-2012Q4. We report the model implied values of investment I_t, the ECB's liquidity injections in terms of quarterly GDP M_t/Y_t, the liquidity spread R_{bt}/R_t, and the bank lending spread R_{kt}/R_t (solid lines). For all variables the figure depicts the change in the data relative to their pre-crisis values (dashed line).[15] Since we assume that in 2007Q2 all variables start at their steady state values, we normalize the data for comparison. Note that we report our measure of liquidity spread identified in Section 2 and not the Euribor-OIS spread. For investment Figure 5 reports not only the raw data (the dashed line), but also a grey shaded area corresponding to different assumptions on this variable's trend. We consider two alternative measures of the trend, derived either from the HP-Filter (over the sample 1999Q1-2014Q3) or by estimating a linear pre-crisis trend (over the sample 1999Q1–2007Q2).[16] The shaded area represents deviations from these two trends normalized to be zero in 2007Q2. Since we do not want to take a stand on whether the trend has changed due to the Great Recession, we report these different possibilities.

Compared with the data, the ECB liquidity injections consistent with our estimated non-standard monetary policy rule would persistently increase during the first six quarters. The actual liquidity injections, in contrast, increase more slowly. Hence,

[15] For the spreads as well as the ECB's liquidity operations, these pre-crisis values are averages over the period 2001Q1-2007Q2. For the non-stationary series investment, we take the value of 2007Q2.

[16] The latter approach is also taken by Christiano et al. (2015).

in this initial phase of the crisis the ECB appears to have been more conservative than over the total period considered in our analysis. In 2010 and 2011 the rule tracks very closely the actual dynamics of the ECB's non-standard measures. With the introduction of Very Long-Term Refinancing Operations at the end of 2011, actual liquidity injections increase sizably to much larger levels than implied by our estimated rule. This finding is consistent with the estimated balance sheet shocks in Boeckx et al. (2017).

By construction, the model matches perfectly the liquidity spread R_{bt}/R_t. It captures well the transmission of the shock through the banking sector which is apparent from the bank lending spread R_{kt}/R_t. Given this good fit of the dynamics of lending rates, we can now assess the liquidity shock's implications on aggregate investment. The fall in investment is sizable. Investment starts edging down already during the financial turmoil in 2007 and then falls persistently down to a trough of 6 percentage points. All in all, according to our model, the liquidity shock accounts for a large share of the actual drop in investment observed during the financial crisis. Depending on the different assumptions about trend investment, this share varies between one third and two thirds.

As a final step, we can use the simulations of the financial crisis to ask again what would have been the macroeconomic impact of the liquidity shock if the ECB had not implemented its non-standard policy. As in the previous section, we set to zero all monetary injections implied by equation (13). Figure 6 shows that the recession in the euro area would have been much more severe without the ECB's non-standard measures. Without this intervention, liquidity spreads would have been at least 200 basis points higher. Around the Lehman bust, liquidity spreads would have been almost 700 basis point higher, which would have translated into an increase in lending spreads of about equal size. Compared with the seven percentage points drop in the benchmark, investment would have fallen by over 15 percentage points in the absence of the ECB intervention.

All in all, our results suggest that the non-standard measures implemented by the ECB had a powerful role in attenuating the real consequences of the financial crisis.

6 Conclusions

In this paper we have presented an analysis for the financial crisis in the euro area based on shocks to interbank liquidity. We have found that a widening of liquidity spreads due to increases in liquidity risk was met by an increase in the amount of central bank liquidity. Nevertheless, it led to larger lending spreads and thus to a tightening of lending conditions for the private sector and to a reduction in economic activity, especially in investment. As a widening of interbank spreads during the financial crisis has not only been caused by increases in liquidity risk, in a first step we have identified the component of interbank spreads which were orthogonal to proxies for counterparty risk and economic uncertainty. In order to compute the counterfactual no-policy scenario, in which the ECB would not have implemented its non-standard measures, we have used these empirical findings to calibrate a structural general equilibrium model. Our structural model is based on a fairly standard New Keynesian model which we have augmented with financial frictions and an explicit characterization of the interbank market. We assume that the tightening of the interbank market friction in the structural model corresponds to the liquidity shock we have identified before.

Through the eyes of our structural model, we have shown that the tensions in the money market were a major determinant of the dynamics of investment during the Great Recession in the euro area. The liquidity injected by the ECB played an important role in attenuating the macroeconomic impact of the shock. Without this intervention, interbank spreads would have been at least 200 basis points higher and their adverse impact on investment would have been more than twice as severe.

Our study has focused on the impact of liquidity shocks, but it does not deny the importance of other shocks in explaining the crisis. In fact, the impact of liquidity shocks on inflation and aggregate consumption is estimated to be very minor. In the model, this feature is starkly captured by the assumption that lending spreads have no impact on households' consumption. A direct implication of this finding is that other shocks, such as variations in bankruptcy costs, the destruction of bank capital associated with the collapse in asset-backed securities and flight-to-safety considerations, must have also played a role during the Great Recession.[17]

Our study has also abstracted from the asymmetric effects of the European financial

[17] See Christiano et al. (2015) for an analysis arguing that these factors played an important role in the United States.

crisis across euro area countries. These effects were certainly part of the euro area experience. Garcia-de-Andoan et al. (2016) documents the differential severity of interbank liquidity shortages in different countries, especially during the sovereign debt crisis. Concerns about "financial fragmentation" were also prominent in the policy debate during this period. Future research on the consequences of financial disruptions in an open economy context would be desirable. From the modelling perspective, it would require a richer framework, capable of accounting for other potential sources of cross-country differences in credit and sovereign spreads.

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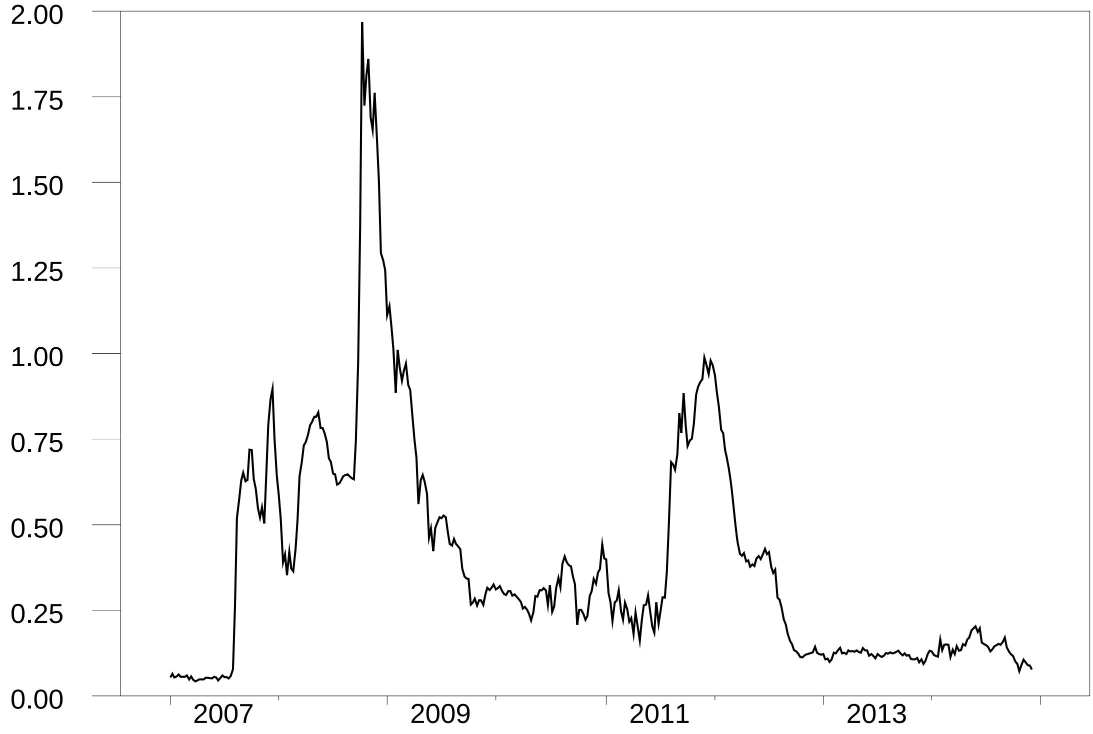


NOTE: The figure shows the spread between 3-month (uncollateralised) Euribor rates and the rate on 3-month overnight index swaps (OIS) (weekly frequency).

Figure 1: Euro Area Interbank Spread (in percent per annum)

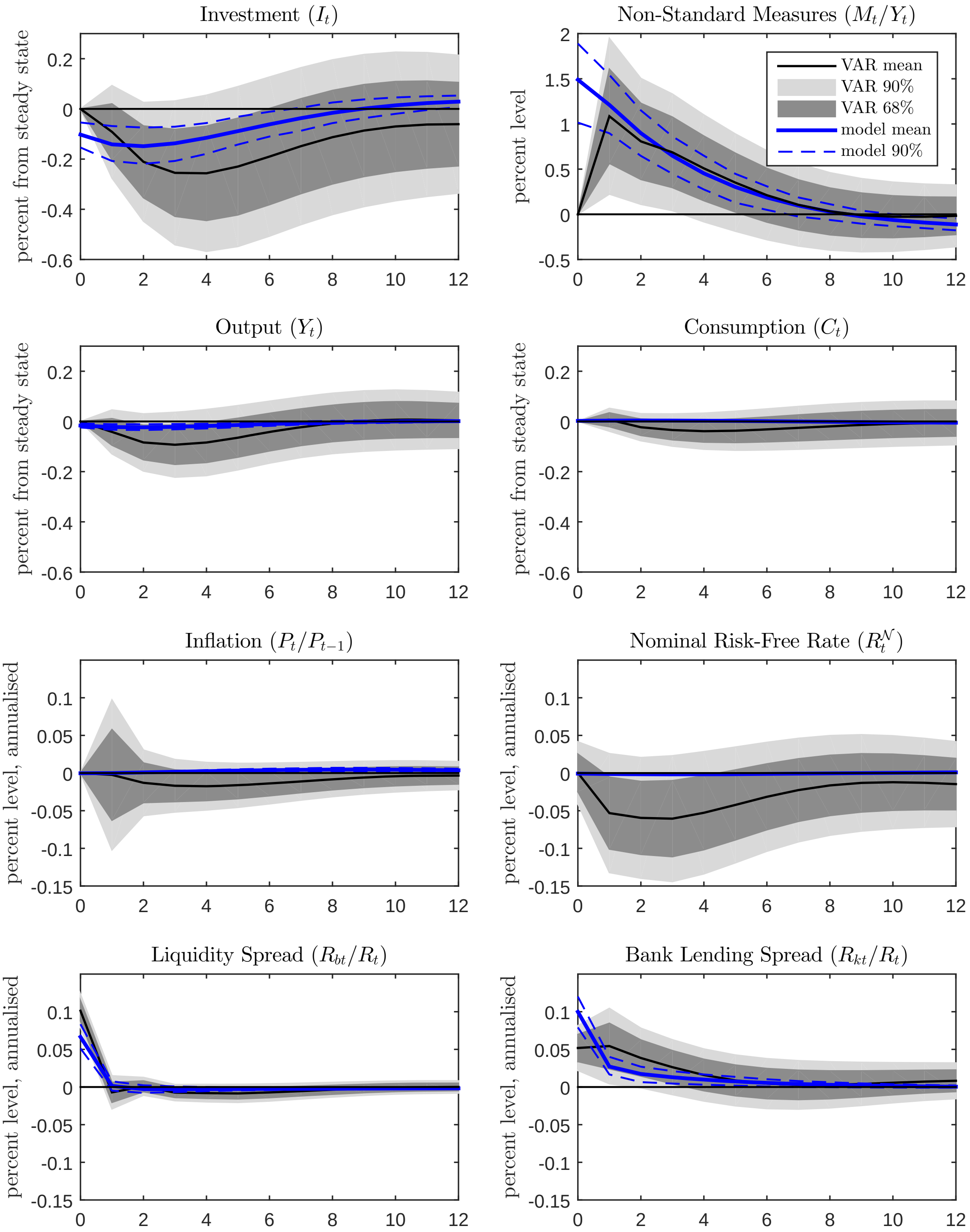


Figure 2: VAR and model-implied impulse response to a liquidity shock

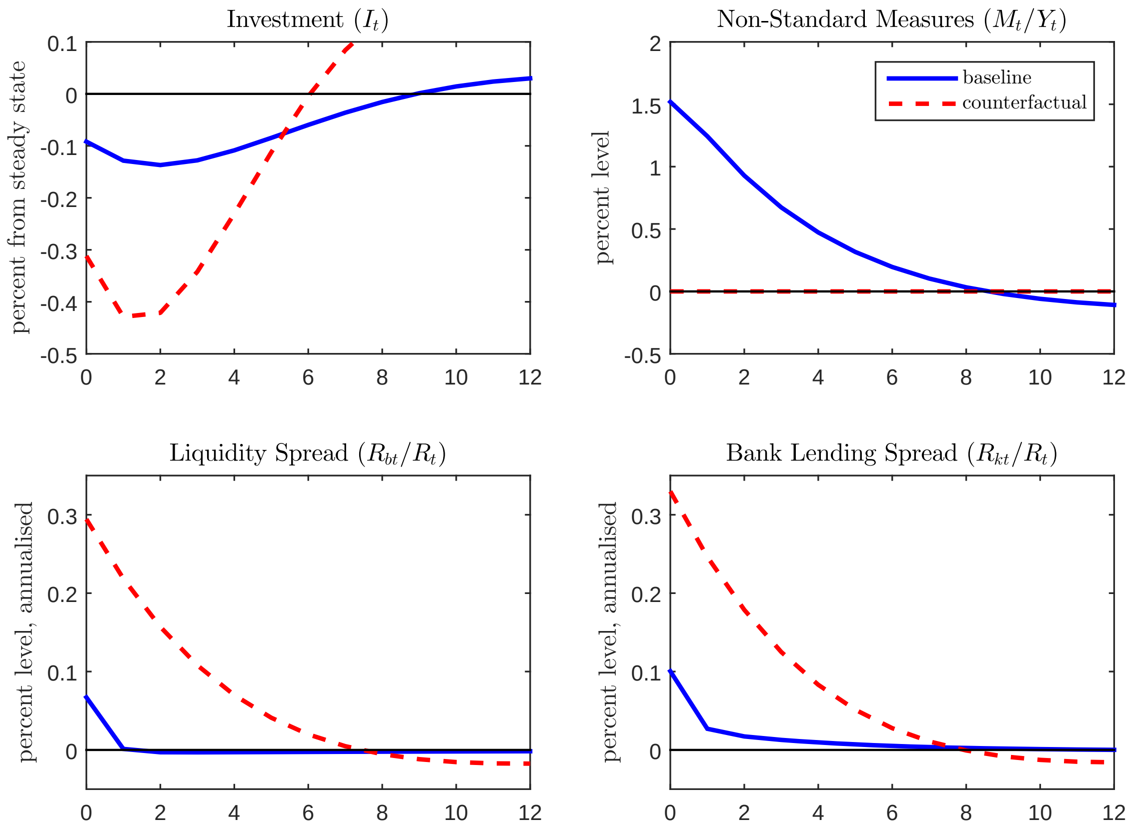


Figure 3: Model-implied impulse response in the counterfactual no-policy scenario

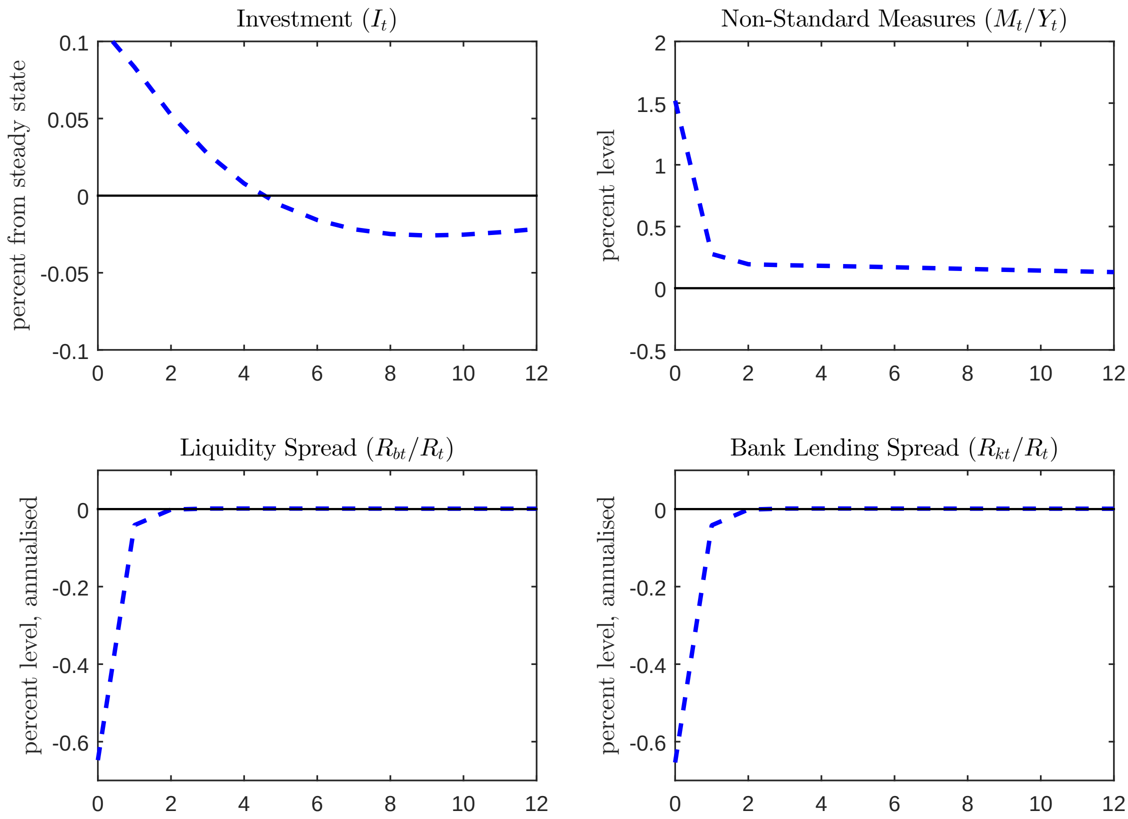


Figure 4: Model-implied impulse response to a non-standard policy shock

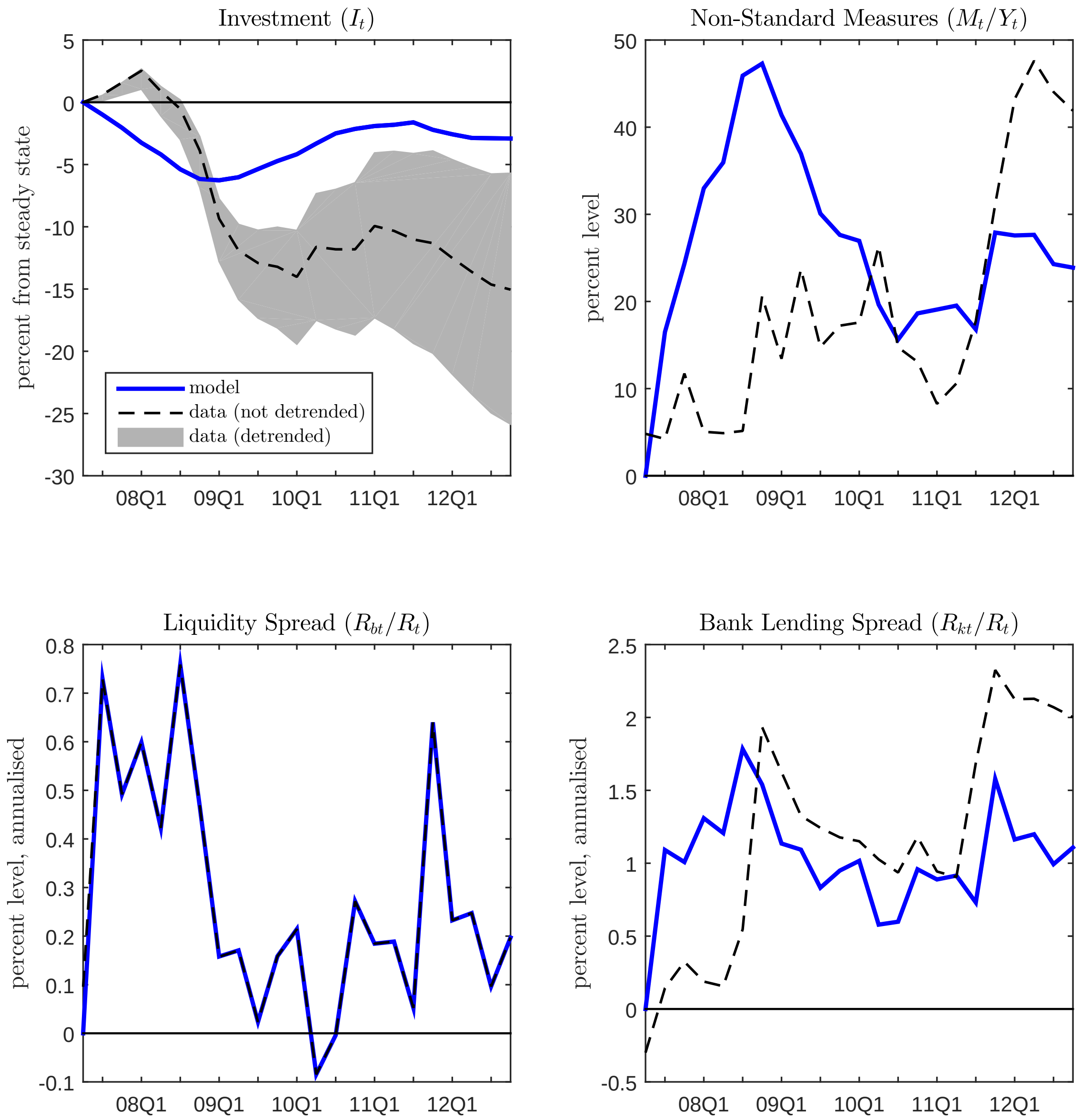


Figure 5: Model-implied contribution of liquidity shocks to investment dynamics

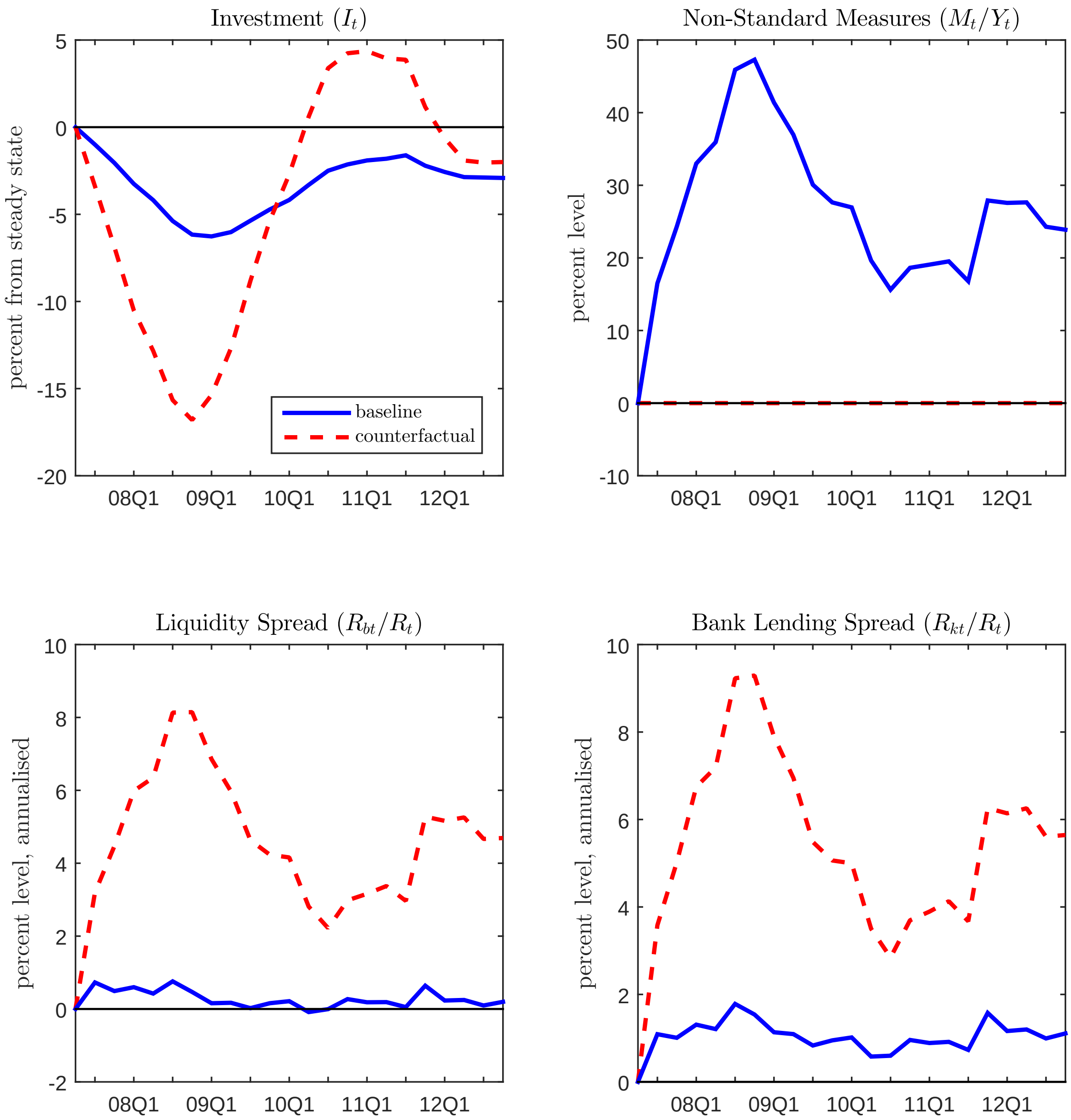


Figure 6: Model-implied simulation of the counterfactual no-policy scenario 2007–2012

Table 1: Factors affecting the interbank market spread

Variable	Coeff	StdError	T-Stat	Signif
Constant	−0.00059	0.00011	−5.60	0.00
VSTOXX	0.02541	0.00200	12.69	0.00
DE CDS	−0.00165	0.00174	−0.95	0.34
FR CDS	0.00321	0.00124	2.60	0.01
ES CDS	−0.00172	0.00030	−5.63	0.00
IT CDS	−0.00003	0.00035	−0.08	0.94
EU Banks CDS	0.00145	0.00051	2.83	0.00

Note: Based on weekly data from 2007:01:05 To 2014:12:05. Newey-West standard errors. $\overline{R}^2 = 0.6944$. Variables are measured in quarterly units.
Legend: "VSTOXX" is a measure of implied volatility derived from EURO STOXX 50 Index Options; "EU Banks CDS" is the Median Spread between CDS Senior Debt 5-year and CDS Subordinated Debt 5-year for the European Union Large Banking Groups; "DE CDS", "FR CDS", "ES CDS" and "IT CDS" are CDS US dollar senior debt 5-year for Germany, France, Spain and Italy, respectively.

Table 2: Calibrated Parameters

Households		
β	0.990	discount factor
h	0.592	habit parameter
φ	2.503	inverse Frisch elasticity
Non-Financial Sector		
α	0.300	capital share
δ	0.025	depreciation rate
θ_p	0.905	Calvo probability prices
χ_p	0.477	indexation of prices
θ_w	0.742	Calvo probability wages
χ_w	0.728	indexation of wages
ε_y	10.00	elasticity of substitution between retail goods
ε_l	3.000	elasticity of substitution between labour
Financial Sector		
σ	0.972	survival rate of bankers
ξ	0.002	transfer to entering bankers
θ	0.408	fraction of divertable assets
$\bar{\omega}$	0.990	average degree of interbank market frictions
ω_m	0.990	fraction of non-divertable central bank assets
Government		
γ_π	1.688	Taylor rule inflation coefficient
$\gamma_{\Delta\pi}$	0.151	Taylor rule inflation growth coefficient
γ_y	0.098	Taylor rule output gap coefficient
$\gamma_{\Delta y}$	0.158	Taylor rule output gap growth coefficient
γ_R	0.956	Taylor rule smoothing parameter

Table 3: Prior and Posterior Distributions

	Parameters	Priors			Posterior	
			Mean	SD	Mean	95% C.S.
η	investment adjustment costs	Gamma	1.00	0.50	1.25	[0.50,1.94]
γ_n	fraction of firms without investment opportunities	Beta	0.75	0.1	0.82	[0.76,0.88]
γ_{R_b}	coefficient non-standard policy rule	Normal	100	20.0	90.51	[62.23,118.43]
ρ_M	persistence non-standard policy rule	Beta	0.75	0.10	0.80	[0.70,0.90]
ρ_ω	persistence liquidity shock	Beta	0.75	0.10	0.79	[0.71,0.87]
σ_ω	std. dev. liquidity shock	Gamma	0.10	0.05	0.03	[0.02,0.04]

A Data and Sources

Our estimation in Section 2 is done in two steps. First, we compute a measure of liquidity spreads which is not contaminated by the effects of uncertainty shocks or counterparty risk. To do so, we use weekly data ranging from 2007w1-2014w52. This dataset includes:

interbank market spread: difference between the 3-month Euribor and the 3-month overnight index swap rate; end-of-period data; Source: ECB

VSTOXX index: measure of implied volatility derived from options on the Dow Jones EURO STOXX 50 Index; end-of-period data; Source: Bloomberg

CDS spreads: EU Banks CDS is the median spread between CDS Senior Debt 5-Year and CDS Subordinated Debt 5-Year for the European Union Large Banking Groups; DE CDS, FR CDS, ES CDS, and IT CDS are CDS US Dollar Senior Debt 5-year for Germany, France, Spain, and Italy, respectively; end-of-period data; Source: Thomson Reuters Datastream

In a second step, we estimate a VAR. The quarterly dataset runs from 2001q1–2014q3 and includes:

GDP: gross domestic product; in log; constant prices; seasonally and working day adjusted; euro area (changing composition); Source: Eurostat

consumption spending: final consumption of households and non-profit institutions serving households (NPISH); in log; constant prices; seasonally and working day adjusted; euro area (changing composition); Source: Eurostat

investment spending: gross fixed capital formation; in log; constant prices; seasonally and working day adjusted; euro area (changing composition); Source: Eurostat

core inflation: quarterly gross inflation rate; Harmonized Index of Consumer Prices (HICP); all items excluding energy and unprocessed food; seasonally adjusted, not working day adjusted; euro area (changing composition); Source: ECB

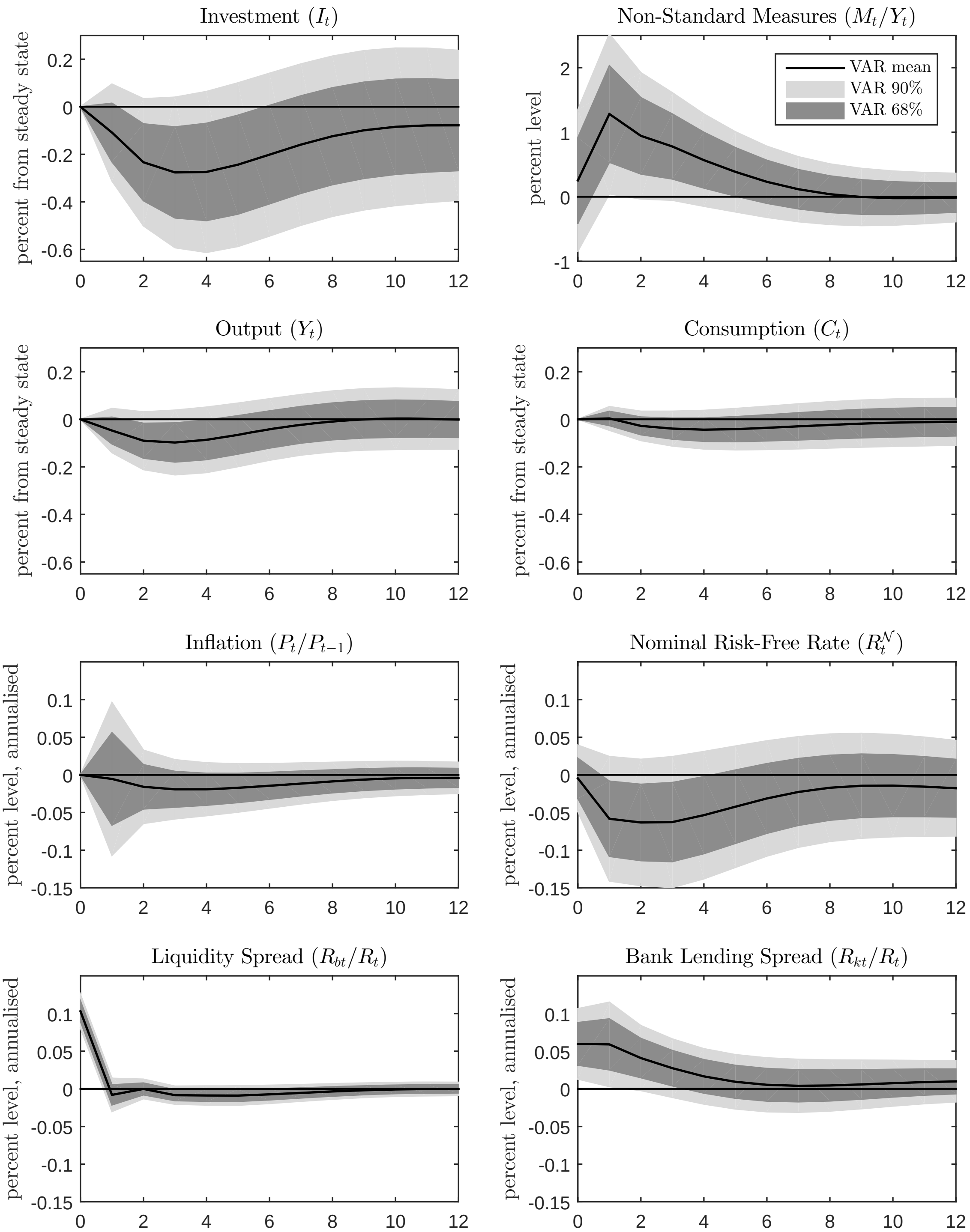
bank lending spread: difference between bank lending rate and 3-month overnight index swap rate: bank lending rate given by interest rates on loans to non-financial corporations (new business) for loans over EUR 250.000 and up to EUR 1 million, maturity: over 3 month and up to 1 year; end-of-period data; Source: ECB

ECB liquidity operations: sum of two items from the Eurosystem balance sheet, relative to GDP: lending to euro area credit institutions related to monetary policy operations and securities held for monetary policy purpose; neither seasonally nor working day adjusted; end-of-period data; Source: ECB

ECB policy rate: 3-month overnight index swap rate; end-of-period data; Source: Thomson Reuters Datastream

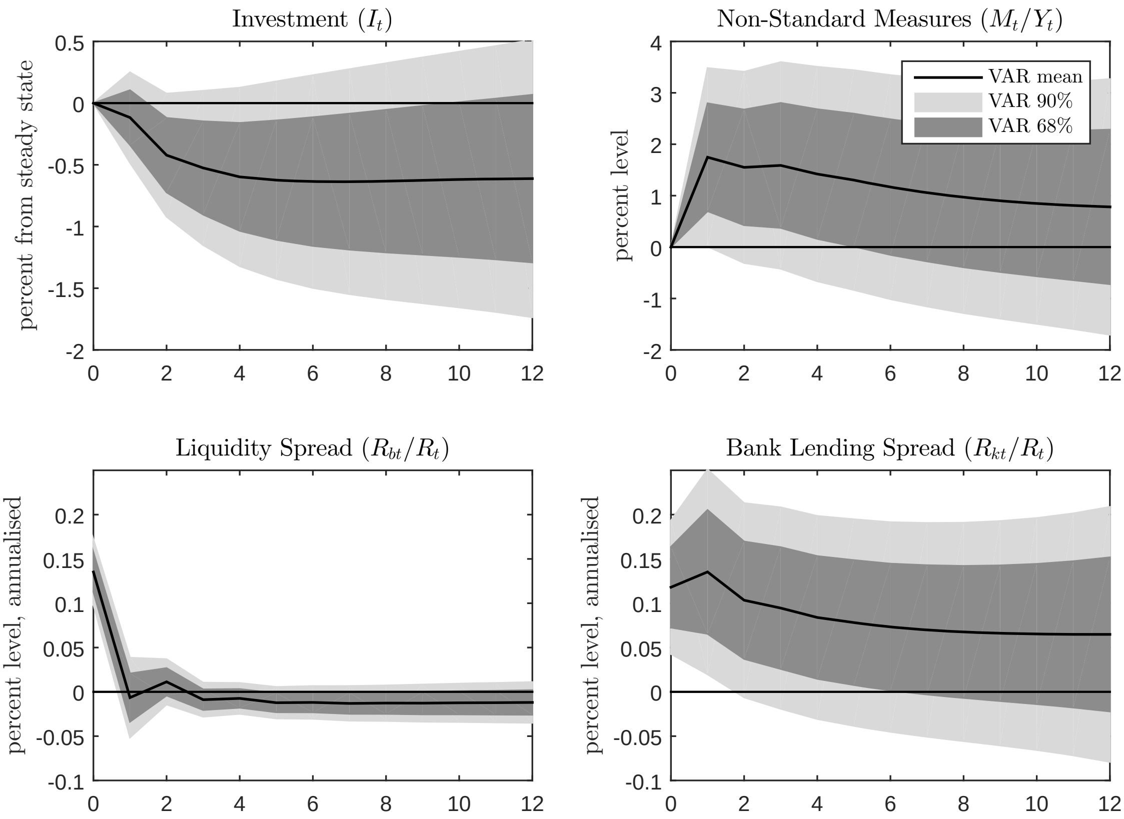
liquidity spread: as explained in the text, this spread is equal to the Euribor-OIS spread for the period 2001–2006 and equal to the measure of liquidity spread computed in the first step from 2007 onwards

B Additional Results



NOTE: The ordering of variables in this estimation is as follows: GDP Y_t, consumption C_t, investment I_t, inflation P_t/P_{t-1}, liquidity spread R_{bt}/R_t, non-standard liquidity measures M_t/Y_t, bank lending spread R_{kt}/R_t, the ECB policy rate R_t.

Figure B.1: VAR impulse response to a liquidity shock—different Cholesky ordering



NOTE: Estimation over the 2007Q1–2014Q3 period using only a subset of variables. The ordering of variables in this estimation is as follows: investment I_t, non-standard liquidity measures M_t/Y_t, liquidity spread R_{bt}/R_t, bank lending spread R_{kt}/R_t.

Figure B.2: VAR impulse response to a liquidity shock—shorter sample

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