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by Dario Bonciani and Björn van Roye

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JEL classification: E32, E52.
Kiel Institute for the World Economy,
24100 Kiel, Germany
Telephone: +49-8814-225

E-mail:
bjoern.vanroye@ifw-kiel.de

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† Contact: Hindenburgufer 66, 24105 Kiel, Germany. E-Mail: Bjoern.vanRoye@ifw-kiel.de Tel: +49(0)431 8815 225

1 Introduction

The negative effect of uncertainty on economic activity is a prevalent topic in both economic policy and academic research. Policy makers and economists have repeatedly claimed that high macroeconomic uncertainty among investors hinders the economy to recover. While there has been a vastly growing literature on the macroeconomic effects of uncertainty shocks, led by the seminal paper by Bloom (2009), there has been relatively little research on the effects of uncertainty shocks under financial frictions. In particular, the existing literature has not yet explained the relationship between uncertainty shocks and frictional banking markets. This chapter tries to fill this gap by investigating the effects of uncertainty shocks when banks operate in monopolistic competition and there is an imperfect pass-through of the central bank's policy rate to both the deposit and the loan rate. Both frictions have been shown to be theoretically and empirically important at business-cycle frequency.[1]

Our contribution is threefold: first, we provide an empirical motivation for the study of uncertainty shocks. Therefore we estimate a small Bayesian Vector Autoregressive (BVAR) model and show that higher uncertainty reduces main macroeconomic aggregates in the euro area. Secondly, we analyze the effects of uncertainty shocks on business cycle fluctuations using a Dynamic Stochastic General Equilibrium (DSGE) model which incorporates nominal rigidities and financial frictions. We build a multi-sector model featuring credit frictions and borrowing constraints for entrepreneurs as in Iacoviello (2005) and price rigidities as in Rotemberg (1982). Moreover, the model is augmented by a stylized banking sector inspired by Gerali et al. (2010). The main results of our analysis is that frictions in the banking sector considerably amplify the negative effects of uncertainty shocks on economic activity and make uncertainty shocks more persistent than otherwise. Thirdly, we reconcile the stronger effects of uncertainty shocks found in the data, compared with the relatively little ones obtained with our DSGE model. We explain that there could be strong nonlinear effects due to the financial crisis and show that in a recession the impact of uncertainty shocks

[1] The importance of monopolistic competition in the banking sector has been extensively documented in the microeconomic literature (see for instance Klein (1971) and Monti (1972)). In addition, there is vast empirical evidence for imperfect pass-through of the monetary policy rate to the retail rates (see for instance Sorensen and Werner (2006) and Gerali et al. (2010)).

is potentially much larger.

The relationship between macroeconomic uncertainty shocks and economic activity is widely analyzed in academic research. Economic theory provides a comprehensible framework in which higher uncertainty affects economic activity through irreversible investments, marginal revenues and precautionary savings (Bernanke (1983), Hartman (1976) and Abel (1983), Leland (1968) and Kimball (1990)). While almost all academic research papers find significant negative effects of uncertainty shocks on key economic variables in a partial equilibrium setup, the effects in a general equilibrium are more disputed. While Bachmann and Bayer (2011) claim there are no significant effects of uncertainty shocks in general equilibrium, Basu and Bundick (2011) claim that there are, given that prices are sticky and the central bank is constrained by the zero lower bound. Born and Pfeifer (2011) analyze the contribution of monetary and fiscal policy uncertainty shocks in the United States during the Great Recession. They show that while policy uncertainty can be found in the data, it is unlikely to have played a large role driving business cycle fluctuations. They find even smaller effects of uncertainty shocks to total factor productivity (TFP). Leduc and Liu (2012) study the macroeconomic effects of uncertainty shocks in a DSGE model with labor search frictions and sticky prices. They show that uncertainty shocks act like aggregate demand shocks since they increase unemployment and reduce inflation.

Albeit there is a a vast growing literature on the effects of uncertainty shocks, only few researchers have analyzed their impact of under financial frictions. Gilchrist et al. (2010) show, both empirically and theoretically, how time-varying uncertainty interacts with financial market frictions in dampening economic fluctuations. Using a standard bond-contracting framework, they find that an increase in uncertainty is beneficial to equity holders while it is costly for bond holders, since uncertainty shocks leads to an increase in the cost of capital and ultimately to declining investment. In addition, decreasing credit supply hinders efficient capital reallocation which leads to a further decrease in TFP. Christiano et al. (2010) apply a DSGE model incorporating the financial accelerator mechanism originally proposed by Bernanke et al. (1999) (BGG) and estimate it for the U.S. economy. They find that risk shocks (i.e., changes in the volatility of cross-sectional idiosyncratic uncertainty) play an important role for shaping U.S. business cycles. While Christiano et al. (2010) exclusively analyze idiosyncratic uncertainty shocks, Balke et al. (2013) also investigate the effects of macroeconomic uncertainty shocks under credit frictions. Using a model with agency costs, they show that the financial accelerator amplifies the contractionary effects under price stickiness. In equal measure, Cesa-Bianchi and Fernandez-Corugedo (2013) show that credit frictions amplify the negative impact of uncertainty shocks on output, investment and consumption. They employ a modified version of the financial accelerator model as in Faia and Monacelli (2007). In addition, they find that micro uncertainty shocks seem to be quantitatively more important than a macro uncertainty shocks. This strand of literature using DSGE models based on the financial accelerator mechanism focuses only on frictions that characterize the demand side of the financial sector.

In this chapter, in contrast, we show that supply side constraints in the financial sector also play an important role in amplifying the effects of uncertainty shocks. Accounting for sticky retail interest rates determines an imperfect pass-through of the central bank interest rate to the private sector. The transmission mechanism of the monetary policy is hence weakened and less effective in offsetting the dampening effects of the uncertainty shock. This study is most closely related to Basu and Bundick (2011), Christiano et al. (2010), and Balke et al. (2013). While Basu and Bundick (2011) use a standard New Keynesian model to show the effects of aggregate uncertainty, we assume that entrepreneurs are credit constrained and that lending is implemented through an imperfectly competitive banking sector.

The rest of the chapter is organized as follows. In section 2 we present empirical evidence of the effects of uncertainty shocks on economic activity by estimating a small BVAR model for the euro area. In section 3 we present short theoretical channels through which uncertainty shocks transmit to economic activity and provide simple economic intuitions. In section 4 we present the DSGE model with borrowing constrained entrepreneurs and a banking sector that is monopolistically competitive. In section 5 we describe the solution method and simulate the model deriving the main channel through which overall uncertainty transmits via the banking sector to the real economy and drives business cycle fluctuations.

Finally, we present concluding remarks in section 6.

2 Empirical evidence

In order to provide evidence on the relevance of uncertainty shocks on economic fluctuations, we estimate a small BVAR model using euro area data.

2.1 Data

As a proxy for aggregate macroeconomic uncertainty we use an index that is derived from the volatility of financial market variables in the euro area. In particular, we use the VSTOXX which provides a measure of market expectations of short-term up to long-term volatility based on the EuroStoxx50 options prices.[2]

In order to investigate the effects of aggregate macroeconomic uncertainty for business cycle fluctuations, we collect further data from the Area Wide model database. We collect data for real GDP, fixed asset investment, the money market rate and the loan rate to non-financial corporations. A detailed description of the data can be found in the appendix.

2.2 Evidence from a BVAR model

To investigate the effects of uncertainty on economic dynamics in the euro area we estimate a small BVAR model with orthogonalized shocks to macroeconomic uncertainty. The available data sample for the euro area is relatively short. We estimate the model with quarterly data starting in 2003.[3] Against this background, we choose to estimate the model with Bayesian techniques, since sampling errors in estimating error bands for the impulse responses can occur when using a highly over parametrized model (Sims and Zha (1998)). The BVAR model has the following form:

$$y_t = B_1 Y_{t-1} + \cdots + B_p Y_{t-p} + \epsilon_t, \quad \text{where} \quad \epsilon_t \sim \mathcal{N}(0, \Sigma), \tag{1}$$

where $y_t = [VOL_t \ \Delta y_t \ \Delta fai_t \ \Delta c_t \ r_t \ r_t^b]'$ is a vector consisting of the following variables: the implied volatility of EUROSTOXX 50 option prices (VOL_t) as

[2] Basu and Bundick (2011) use a similar implied volatility index for the United States (VIX) in order to identify the uncertainty shock.

[3] The loan rate for non-financial corporations is only available from the beginning of 2003. The other time series are available for a longer time horizon. We also estimated the model with a longer time horizon without the loan rate. The results do not substantially differ from the ones reported here. Results are available upon request.

uncertainty variable, the logarithm of real GDP (y_t) as an indicator for economic activity, the logarithm of fixed asset investment (fai_t), the logarithm of private consumption, the EONIA-money market rate (r_t) as an indicator for the ECB's monetary policy stance and the loan rate r_t^b. $B_1, \ldots, B_p$ are $(q \times q)$ autoregressive matrices and Σ is the $(q \times q)$ variance-covariance matrix. For the prior distribution of the parameters we choose Jeffreys' improper prior to help improve the estimation of error bands for impulse responses. To be precise, the distribution on the parameters B and Σ i given by:

$$p(B, \Sigma) \propto |\Sigma|^{-\frac{ny+1}{2}}. \quad (2)$$

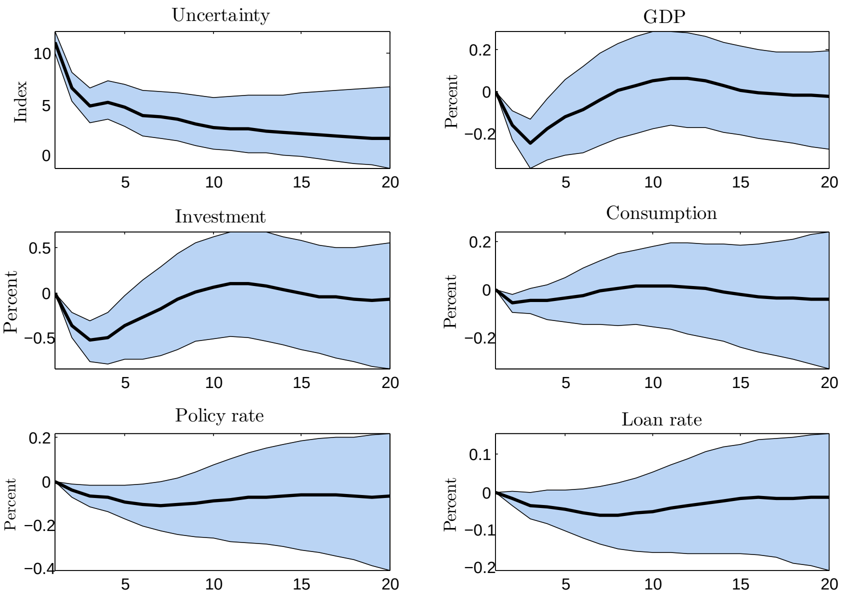
In our baseline model, we choose a lower triangular Choleski identification, ordering the uncertainty index first, such that on impact shocks to the uncertainty index have impact on the real variables. This ordering has been established in a vast majority of the literature (See for example Bloom (2009) and Baker et al. (2012)).[4] Vice versa, we assume that uncertainty is on impact not affected by shocks to the other endogenous variables. The impulse responses are depicted in Figure 1. While the black solid lines are median responses of the endogenous variables to one-standard-deviation increase in the innovations to uncertainty, the shaded areas represent 68 percent confidence intervals.

The IRF indicate that an exogenous increase of uncertainty leads to a persistent decline in real GDP and fixed asset investment. The effect on private consumption, the policy rate and the loan rate are very small, however. The strongest effect of a one-standard deviation increase in uncertainty hits after 4 quarters. While the median responses of GDP is a decline of about 0.2 percent, investment drops by about 0.5 percent. The results are in line with other empirical studies about the effects of uncertainty for other countries.[5] Our results indicate that uncertainty has negative business cycle effects in the euro area.

[4] A different ordering of the variables, in particular when the uncertainty index is ordered last, yields qualitatively similar results. Results are available upon request.

[5] Bloom (2009) and Baker et al. (2012) show in a VAR model that uncertainty leads to a persistent decrease in industrial production in the United States. Denis and Kannan (2013) find persistently negative effects of uncertainty on monthly GDP indicators for the United Kingdom and on economic sentiment indicators.

Figure 1: *Impulse responses after a macro-uncertainty shock*



Notes: The volatility of the VSTOXX is ordered first. The black solid lines are median responses of the endogenous variables to one-standard-deviation increase in the innovations to uncertainty. Shaded areas represent 68 percent error bands.

3 Uncertainty shocks: Economic theory and intuition

The effects of uncertainty shocks on economic activity have been extensively analyzed in the microeconomic literature over the past decades. In particular it has been highlighted that increases in uncertainty affect the economy mainly via three channels (Born and Pfeifer (2011)):

1. Real options channel;
2. Convex marginal revenue product channel;
3. Precautionary savings channel.

The microeconomic effects of these channels are potentially contrasting and are the result of partial equilibrium analysis. In a general equilibrium framework the aforementioned effects may or may not be completely offset. In this section we briefly describe these channels and put them into a general equilibrium context.

Real options channel

The real option channel refers to the option value associated with irreversible investments. In particular, when an investment is utterly or even partially irreversible (i.e. once constructed, it cannot be undone without facing high costs) and the investor has an imperfect information concerning the future returns on long-term projects, there is an option value associated with avoiding such an investment (Bernanke (1983)). The agent who decides to postpone an investment, giving up short-term returns, will have the option in the next period either to invest or to further postpone the expenditure. As the investor is not endowed with perfect foresight on the returns on his investments, waiting and therefore obtaining new relevant information makes it more likely for her to make a better investment decision.

Investment opportunities, arising for instance from patents or from the ownership of land and natural resources, are similar to a financial call option, while investing in capital which may be sold in the future at a higher price, is effectively equivalent to purchasing a put option. A call (put) option is a contract that gives the right to the buyer to purchase (sell) an underlying asset at a predetermined price. When a firm makes an irreversible investment expenditure, it exercises its option to invest, as it gives up the possibility of waiting for new information to arrive that might affect the desirability or timing of the expenditure. It cannot disinvest in case the market conditions change adversely.

Obviously irreversible investments are particularly sensitive to risk concerning future cash flows, interest rates or the future price of capital. Uncertainty has a negative effect on the payoff of the agent owning the "call option" (the investment opportunity), while it has a positive effect on the payoff of the agents owning the "put option" (who already invested and can resell the capital at a predetermined higher price). As a bottom line, the real options effect may dampen economic activity when including investment and capital in our model. This is particularly the case when firms additionally face investment adjustment costs.

Convex marginal revenue product channel

In models with risk-neutral competitive firms with convex adjustment costs, if the marginal revenue product of capital is a strictly convex function of the price of output, then investment is an increasing function of the variance of price and of TFP. This means that increases in uncertainty about the price of output and TFP determines an increase in investment (Hartman (1976); Abel (1983)). All in all, this channel shows that higher uncertainty may result in accelerating investment and a boost in economic activity, which contrasts with the real options channel described above.

Precautionary savings channel

Under the assumption of additivity of the utility function or of decreasing risk aversion, an increase in uncertainty with respect to the future income stream leads to an increase in savings (Leland (1968)). Faced with higher uncertainty, agents reduce their consumption and supply more labor in order to insure themselves against future negative events. In a closed economy, the increase in savings determines a one-to-one increase in investment. Later on, Carroll and Samwick (1998) show that this behavior also holds empirically and that higher uncertainty about household's future income distribution leads to precautionary savings. As a bottom line, the precautionary savings channel may lead to an increase in investment and a decline in consumption. The overall effect on output cannot be determined a priori.

Effects in General Equilibrium

The effects discussed above are potentially contrasting and are the result of partial equilibrium analysis. While in partial equilibrium output and its components generally co-move after an uncertainty shock, this may not be the case in a general equilibrium framework (Basu and Bundick (2011)). The difficulty of generating business cycle co-movements and sizeable effects of uncertainty on major macroeconomic aggregates stems from the endogeneity of the real interest rate. In a standard Real Business Cycle (RBC) model, in which prices are fully flexible and there is no role for monetary policy, consumption falls and labor increases because of precautionary behavior. Given that capital is predetermined, the increase in labor input leads to an increase in output and savings. In a closed economy this implies a hike in investment. In contrast, in a New Keynesian model (NKM), characterized by sticky prices and time varying markups of prices over marginal costs, this is not necessarily the case. After an uncertainty shock, prices do not adjust immediately to changing marginal costs and markups rise as private households supply more labor. As a consequence of the increase in markups, labor demand falls and in equilibrium, hours worked may decline. In turn, output, consumption and investment fall.

In a NKM, however, the monetary authority can partially offset the negative effects of uncertainty by reducing the nominal interest rate. It is most importantly this reason why many papers do not find strong effects of uncertainty shocks on economic activity. A central bank that is aggressively counteracting uncertainty shocks offsets the negative effects on output similarly to other exogenous shocks (Born and Pfeifer (2011)). Also Bachmann and Bayer (2011) show that the endogenous feedback of nominal interest rates and nominal wages mitigate the negative effects on output. When the monetary authority is constrained by the zero lower bound, the effects of uncertainty become much more significant, as the central bank cannot perfectly respond to the shock. Similarly, accounting for frictions in the banking sector affects the transmission mechanism of monetary policy. When changes in the central bank's policy rate are not perfectly passed through to the private sector (by imposing monopolistic competition in the retail banking sector and assuming sticky loan and deposit rates), the offsetting power of the monetary authority is notably undermined. The zero lower bound is a more extreme constraint on the monetary policy than the imperfect pass-through. Nevertheless, it is important to point out that the zero lower bound is constraining under the circumstance of the policy interest rate actually being close to zero. The amplification channel in this chapter occurs also in "normal" times when the interest rate is far from the zero lower bound.

4 The model

We derive a medium-sized DSGE model based on Iacoviello (2005) and Gerali et al. (2010) featuring a frictional banking sector. The economy is populated by two types of agents: households and entrepreneurs. These are heterogeneous in their time preferences, such that in equilibrium, households are net lenders and entrepreneurs are net borrowers. Households maximize their discounted lifetime utility by choosing consumption and labor. They deposit their savings at commercial banks, which remunerate them with an interest rate r^d. In addition, we assume that households own shares of the commercial banks and of the final-good firms (i.e. retail firms).

Entrepreneurs own competitive firms that produce a homogeneous intermediate good by mixing labor services, supplied by the households, and capital that they purchase from capital producers. They sell the intermediate good to retailers, who use it to produce the final consumption good. Entrepreneurs get loans from the banks at a loan interest rate r^b. Their ability to borrow is constrained by the value of their stock of physical capital that is used as collateral. Entrepreneurs are furthermore assumed to own the capital producing firms.

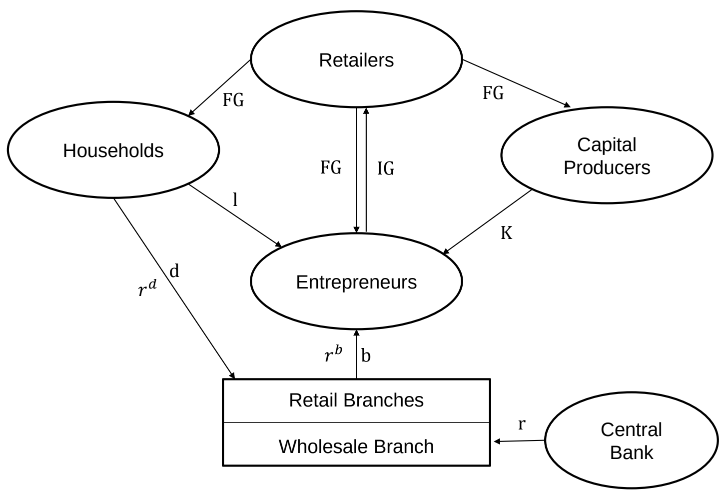
Capital-producing firms combine old undepreciated capital, acquired from the entrepreneurs, and final goods, purchased from the retailers in order to fabricate new capital. Transforming final goods into capital involves adjustment costs. Capital-producing firms sell the new capital back to the entrepreneurs.

Similarly as in Bernanke et al. (1999), price stickiness is introduced at the final-good firms level, with price adjustment costs á la Rotemberg (1982). These firms operate in monopolistic competition. They acquire intermediate goods from the entrepreneurs and produce differentiate final-consumption goods. These differentiation is only marginal, e.g. different brands or different colors.

The model economy features a frictional banking sector. Commercial banks conduct the financial intermediation activities. Each bank consists of two branches: a competitive wholesale branch that manages the capital of the bank and chooses the wholesale amount of deposits and loans; a retail branch that lends resources to entrepreneurs and collects deposits of the households. The retail branch operates in a monopolistically competitive environment and has therefore a certain degree of market power. It can therefore assert a relatively high loan interest rate to the entrepreneurs and a low deposit interest rate to the households with respect to the central bank interest rate, such that $r^d \leq r \leq r^b$. A very important characteristic of the model is the assumption that banks pay adjustment costs when changing the retail interest rates. The stickiness in the retail interest rates determines an imperfect pass-through of the monetary policy rate.

The model accounts for two exogenous shocks: a TFP "level" shock, i.e. a standard first-moment shock to technology, that enters the entrepreneur's production function; a TFP uncertainty shock, i.e. a second-moment shock to technology that enters indirectly the solution of the model. In figure 2 we depict the model economy.

Figure 2: *The model economy*



NOTES: FG denotes the final good and IG the intermediate good.

4.1 Non-financial sector

We assume two different types of non-financial agents, i.e. households and entrepreneurs. Households are more patient than entrepreneurs and are therefore characterized by a higher intertemporal discount factor (i.e. $\beta_h > \beta_e$). This determines that in equilibrium households will be net lenders and entrepreneurs net borrowers.

4.1.1 Households

Each household i chooses consumption $c_t^h(i)$, labor $l_t(i)$ and savings to be deposited at the bank $d_t(i)$ in order to maximize its expected discounted lifetime utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta_h^t \left[log(c_t^h(i)) - \frac{l_t(i)^{1+\phi}}{1+\phi} \right], \tag{3}$$

where ϕ is the inverse of the Frisch labor supply elasticity. Each representative household maximizes its utility subject to its budget constraint:

$$c_t^h(i) + d_t(i) = w_t l_t(i) + \frac{1 + r_{t-1}^d}{(1+\pi_t)} d_{t-1}(i) + J_t^R(i) + (1-\varphi) J_t^B(i). \tag{4}$$

The expenditures of the current period consist of consumption and deposit contracts. The income stream of the households is composed of wage income $(w_t l_t(i))$, real interest payments resulting from last period's deposits made at the bank, deflated by the consumer price inflation $((1 + r_{t-1}^d)/(1 + \pi_t))$, profits of the monopolistically competitive retail sector (J_t^R) and a share $(1-\varphi)$ of profits J_t^B from the monopolistically competitive banking sector which is paid out as dividend.

4.1.2 Entrepreneurs

Entrepreneurs own firms that produce a homogeneous intermediate good. Each entrepreneur j maximizes her lifetime utility choosing consumption $c_t^e(j)$, borrowing $b_t(j)$ and the stock of physical capital $k_t(j)$

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta_e^t \left[\log(c_t^e(j)) \right], \tag{5}$$

subject to:

$$c_t^e(j) + w_t l_t(j) + \frac{1 + r_{t-1}^b}{(1+\pi_t)} b_{t-1}(j) + q_t^k k_t(j) = \frac{y_t^e(j)}{x_t} + b_t(j) + (1-\delta) q_t^k k_{t-1}(j),$$

where r^b represents the loan rate, δ is the capital depreciation rate, and q_t^k the real price of capital. Ultimately, $1/x_t = P_t^W/P_t$ is the relative price of the intermediate good, such that x_t can be interpreted as the gross markup of the final good over the intermediate good. The firm uses a Cobb-Douglas production function given by:

$$y_t^e(j) = z_t[k_{t-1}(j)]^{\alpha} l_t(j)^{1-\alpha}, \tag{6}$$

where z_t represents TFP and α is the share of capital employed in the production process.

As previously mentioned, entrepreneurs are allowed to borrow an amount of resources that is commensurate with the value of physical capital the entrepreneurs own. Hence, they face a borrowing constraint á la Kiyotaki and Moore (1997) that is given by:

$$(1 + r_t^b)b_t(j) \leq m\mathbb{E}_t[q_{t+1}^k(1 + \pi_{t+1})(1 - \delta)k_t(j)], \tag{7}$$

where the left-hand side is the amount to be repaid by the entrepreneur and the right-hand side represents the value of the collateral. In particular m represents the loan-to-value (LTV) ratio.

4.1.3 Capital producers

Capital producing firms are introduced in order to obtain a price for capital that is necessary to determine the value of the entrepreneur's collateral. These firms act in a perfectly competitive market and are owned by the entrepreneurs. They purchase last period's undepreciated capital $(1 - \delta)k_{t-1}$ from the entrepreneurs at a price Q_t^k and i_t units of final goods from retail firms and combine them to produce new capital. In order to transform final goods into capital, these firms face quadratic adjustment costs. The new capital is then sold back to the entrepreneurs at the same price Q_t^k. The real price of capital is defined as $q_t^k \equiv \frac{Q_t^k}{P_t}$. Capital producers maximize then their expected discounted profits:

$$\underset{\{k_t, i_t\}}{max} \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{0,t}^e \left(q_t^k \Delta k_t - i_t \right), \tag{8}$$

subject to:

$$k_t = k_{t-1} + \left[1 - \frac{\kappa_i}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right] i_t, \tag{9}$$

As stated above, entrepreneurs own the capital producing firms. These take as given the entrepreneurs' stochastic discount factor (i.e the intertemporal marginal rate of susbtitution) $\Lambda^e_{0,t} \equiv \frac{\beta_e c^e_0}{c^e_t}$. κ_i governs the magnitude of the adjustment costs associated with the transformation of the final good into capital.

4.2 Retailers

The retailing firms are modeled similarly as in Bernanke (1983). These firms are owned by the households, they act in monopolistic competition and their prices are sticky. They purchase the intermediate-good from entrepreneurs in a competitive market, then slightly differentiate it, e.g. by adding a brand name, at no additional cost. Let $y_t(\nu)$ be the quantity of output sold by the retailer ν, and $P_t(\nu)$ the associated price. The total amount of final good produced in the economy:

$$y_t = \left[\int_0^1 y_t(\nu)^{(\epsilon^y-1)/\epsilon^y} \mathrm{d}\nu\right]^{\epsilon^y/(\epsilon^y-1)}, \tag{10}$$

with the associated price index:

$$P_t = \left[\int_0^1 P_t(\nu)^{(1-\epsilon^y)} \mathrm{d}\nu\right]^{1/(1-\epsilon^y)}. \tag{11}$$

In (10) and (11), ϵ^y represents the elasticity of substitution between differentiated final goods. Given (10), the demand that each retailer faces is equal to:

$$y_t(\nu) = \left(\frac{P_t(\nu)}{P_t}\right)^{-\epsilon^y} y_t. \tag{12}$$

Each firm ν chooses its price to maximize the expected discounted value of profits subject to the demand for consumption goods (12):

$$\max_{\{P_t(\nu)\}} \mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda^h_{0,t} \left[\left(P_t(\nu) - P^W_t\right) y_t(\nu) - \frac{k_P}{2}\left(\frac{P_t(\nu)}{P_{t-1}(\nu)} - (1+\pi)\right)^2 P_t y_t\right], \tag{13}$$

It is assumed that firms take the households' (that own the firms) stochastic discount factor , $\Lambda^h_{0,t} \equiv \frac{\beta_h c^h_0}{c^h_t}$, as given. Prices are assumed to be indexed to steady state inflation. The last term of the objective function represents quadratic adjustment costs the retailer j faces whenever she wants to adjust her prices beyond indexation (Rotemberg (1982)). As we have already mentioned P^W_t represents the price of intermediate goods that the retailers take as given.

4.3 Financial sector

The financial sector consists of commercial banks modeled similarly as in Gerali et al. (2010). Households are the shareholders of these banks. These operate on a wholesale level and on a retail level. The wholesale branch acts in a perfectly competitive market, manages the total capital of the bank and is characterized by the following balance sheet identity:

$$b_t = d_t + k_t^b, \tag{14}$$

which can be graphically represented by:

Banks Balance Sheet

Assets	***Liabilities***
b_t	k_t^b
	d_t

All bank assets consist of loans to firms b_t, whereas liabilities consist of bank capital (net worth) k_t^b, and wholesale deposits d_t.
The retail branch of the bank operates in a monopolistically competitive market and is composed by two divisions:

1. A loan-retail division, which is responsible for lending resources to the entrepreneurs;

2. A deposit-retail division, which collects the deposits of the saving households.

The market power in this market is modeled in a Dixit-Stiglitz fashion. Every loan (deposit) retail branch marginally differentiates the loan (deposit) contract. All these contract are then assembled in a CES basket that is taken as given by entrepreneurs and households. The demand for loans at bank n can be derived by minimizing the total debt repayment of entrepreneur j:

$$\min_{b_t(j,n)} \int_0^1 r_t^b(n) b_t(j,n) \mathrm{d}n, \tag{15}$$

subject to

$$\bar{b}_t(j) \leq \left[\int_0^1 b_t(j,n)^{(\epsilon^b-1)/\epsilon^b} \mathrm{d}n\right]^{\epsilon^b/(\epsilon^b-1)}, \tag{16}$$

where $\bar{b}_t$ is the amount of real loans sought by entrepreneur j and ϵ^b is the elasticity of substitution of loan contracts. The aggregate demand for loans at bank n is then given by:

$$b_t(n) = \left(\frac{r_t^b(n)}{r_t^b}\right)^{-\epsilon^b} b_t. \tag{17}$$

The demand function $b_t(n)$ depends negatively (as ϵ^b is assumed to be larger than 1) on the loan interest rate $r_t^b(n)$ that is set at the retail-division level, and positively on the total amount of loans b_t. The demand for deposits at bank n can be derived similarly by maximizing the total revenue of savings accruing to household i:

$$\max_{d_t(i,n)} \int_0^1 r_t^d(n) d_t(i,n) \mathrm{d}n \tag{18}$$

subject to

$$\bar{d}_t(i) \geq \left[\int_0^1 d_t(i,n)^{(\epsilon^d-1)/\epsilon^d} \mathrm{d}n\right]^{\epsilon^d/(\epsilon^d-1)}, \tag{19}$$

where $\bar{d}_t(i)$ is the amount of real deposits sought by household i and ϵ^d is the elasticity of substitution of deposit contracts. The aggregate demand for loans at bank n is equal to:

$$d_t(n) = \left(\frac{r_t^d(j)}{r_t^d}\right)^{-\epsilon^d} d_t. \tag{20}$$

The demand function $d_t(n)$ depends positively both on the deposit rate r_t^d that is set by the deposit retail-division, (since ϵ^d is assumed to be smaller than 1) and on the total volume of resources deposited in the bank d_t.

4.3.1 Wholesale branch

As mentioned above, the wholesale banking market is perfectly competitive. The wholesale branch of each bank maximizes the discounted sum of cash flows by choosing wholesale loans and deposits, b_t and d_t, taking into account the stochastic discount factor of the households $\Lambda^h_{0,t}$:

$$\underset{\{b_t,d_t\}}{max}\mathbb{E}_0\sum_{t=0}^{\infty}\Lambda^h_{0,t}\Big[(1+R^b_t)b_t-(1+\pi_{t+1})b_{t+1}+d_{t+1}-(1+R^d_t)d_t+(K^b_{t+1}(1+\pi_{t+1})-k^b_t)\Big], \tag{21}$$

subject to the budget constraint:

$$b_t = d_t + k^b_t, \tag{22}$$

and given the following law of motion for bank capital:

$$(1+\pi_t)k^b_t = (1-\delta^b)k^b_{t-1} + \varphi J^b_{t-1}. \tag{23}$$

It is moreover assumed that banks can obtain unlimited funding from the central bank at the policy rate r_t. The no-arbitrage condition hence implies that the wholesale deposit and loan rates coincide with r_t:

$$R^b_t = R^d_t = r_t. \tag{24}$$

4.3.2 Retail branch

Retail banks, in both loan and deposit activities, operate in monopolistic competition and are therefore profit maximizers. Loan-retail divisions maximize their expected discounted profits by choosing the interest rate on loans and facing quadratic adjustment costs. These banks borrow liquidity from the wholesale branch at rate R^b_t (which as we previously showed is equal to the policy rate) and lend it to the entrepreneurs at rate $r^b_t(n)$. The optimization problem of the loan-retail division of bank n is given by:

$$\mathbb{E}_0\sum_{t=0}^{\infty}\Lambda^h_{0,t}\left[\left(r^b_t(n)-r_t\right)b_t(n)-\frac{\kappa_b}{2}\left(\frac{r^b_t(n)}{r^b_{t-1}(n)}-1\right)^2 r^b_t b_t\right], \tag{25}$$

subject to the demand for loans (17).

Deposit-retail divisions maximize their profits by choosing the interest rate r^d_t

which they pay on households' deposits. Their activity consists in collecting the households' deposits and lend those resources to the wholesale bank that pays an interest rate R_t^d (equal to r_t) on them. The optimization problem of the deposit division of bank n is:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Lambda_{0,t}^h \left[\left(r_t - r_t^d(n)\right) d_t(n) - \frac{\kappa_d}{2} \left(\frac{r_t^d(n)}{r_{t-1}^d(n)} - 1 \right)^2 r_t^d d_t \right], \tag{26}$$

where $d_t(n)$ are the wholesale deposits of bank n. The optimization problem is constrained by the demand for deposits of the households (20).

4.4 Monetary Authority

The central bank sets the nominal interest rate following a conventional Taylor type rule:

$$\frac{1+r_t}{1+r} = \left(\frac{1+r_{t-1}}{1+r} \right)^{\phi_r} \left[\left(\frac{1+\pi_t}{1+\pi} \right)^{\phi_\pi} \left(\frac{y_t}{y_{t-1}} \right)^{\phi_y} \right]^{(1-\phi_r)}, \tag{27}$$

where ϕ_r is a smoothing parameter that captures the gradual movements in the interest rate as in Clarida et al. (1999), r and π are respectively the steady state values of the policy rate and of inflation. ϕ_π and ϕ_y represent the weights the central bank gives to deviations of inflation from its steady state level and to output growth.

4.5 Market clearing

Ultimately the model is closed by combining the first order conditions of all agents to the clearing condition of the goods market:

$$y_t = c_t + [k_t - (1-\delta)k_{t-1}] + \delta^b \frac{k_{t-1}^b}{(1+\pi_t)} + ADJ_t, \tag{28}$$

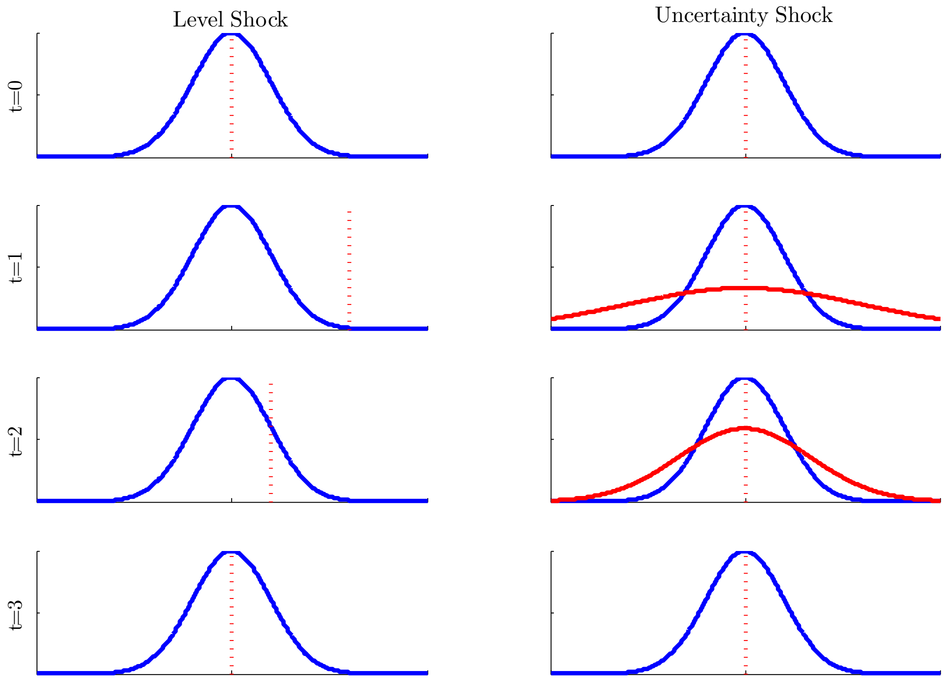
where $c_t \equiv c_t^h + c_t^e$ is aggregate consumption, k_t is aggregate physical capital and k_t^b, as mentioned before, represents aggregate bank capital. Ultimately ADJ_t includes all real adjustment costs for prices and interest rates:

$$ADJ_t \equiv \frac{\kappa_p}{2}(\pi_t)^2 y_t + \frac{\kappa_d}{2} \left(\frac{r_{t-1}^d}{r_{t-2}^d} - 1 \right)^2 r_{t-1}^d d_{t-1} + \frac{\kappa_b}{2} \left(\frac{r_{t-1}^b}{r_{t-2}^b} - 1 \right)^2 r_{t-1}^b b_{t-1}. \tag{29}$$

4.6 Shock processes

In order to model uncertainty shocks, we use the stochastic volatility approach as proposed by Fernandez-Villaverde et al. (2011), assuming time varying volatility of the innovation to TFP. An uncertainty shock is a second-moment shock that affects the shape of the distribution by widening the tails of the level shock and keeping its mean unchanged. A level shock is a first-moment shock that varies the level of TFP, keeping its distribution unchanged. A graphical comparison between the two types of shocks is shown in figure 3.

Figure 3: *Level and uncertainty shock*



Notes: The left column represents a level shock to TFP. The right column represents a second moment shock. We assume the shock to die out in period $t = 3$.

The red dotted line represents the level of TFP that increases after a positive TFP level shock and returns to its initial level only after three periods. With a positive uncertainty shock, instead, the level of TFP remains constant, while its distribution becomes wider as the variance of the TFP shock increases. As the effect of the shock dissipates, the distribution returns to its initial shape.

The stochastic volatility approach ensures that the dispersion of the level shocks varies over time, such that there are sometimes large shocks and other times less intensive ones. We consider an exogenous shock to the volatility of TFP, that can also be interpreted as supply-side uncertainty. TFP follows an AR(1) process with time-varying volatility of the innovations:

$$z_t = (1 - \rho_z)z + \rho_z z_{t-1} + \sigma_t^z e_t^z. \tag{30}$$

The coefficient $\rho_z \in (-1, 1)$ determines the persistence of the TFP level shock. The innovation to the TFP shock, e_t^z, follows an *i.i.d.* standard normal process. Furthermore the time-varying standard deviation of the innovations, σ_t^z, follows the stationary process:

$$\sigma_t^z = (1 - \rho_{\sigma^z})\sigma^z + \rho_{\sigma^z}\sigma_{t-1}^z + \eta_z e_t^{\sigma_z}, \quad \text{where } e_t^{\sigma_z} \sim \mathcal{N}(0, 1) \tag{31}$$

in which ρ_{σ^z} determines the persistence of the uncertainty shock, σ^z is the steady state value of σ_t^z and η_z is the (constant) standard deviation of the TFP uncertainty shock, $e_t^{\sigma_z}$.

5 Macroeconomic effects of uncertainty

5.1 Solution and simulation method

The model is solved with the algorithm and software developed by Lan and Meyer-Gohde (2011). Their solution method consists of a nonlinear moving average perturbation technique that maps our nonlinear DSGE model:

$$\mathbb{E}_t f(x_{t+1}, x_t, x_{t-1}, e_t) = 0, \tag{32}$$

into a system of equations, known as policy function:

$$x_t = h(\sigma, e_t, e_{t-1}, e_{t-2}, \dots). \tag{33}$$

In (32) and (33), x_t and e_t represent the vectors of endogenous (control and state) variables and exogenous shocks. $\sigma \in [0, 1]$ denotes a scaling parameter for the distribution of the stochastic shocks e_t, such that $\sigma = 1$ corresponds to the original stochastic model (32), and $\sigma = 0$ to the non-stochastic case. The basic idea behind this solution method is to approximate the policy function with Volterra series expansion around the deterministic steady state:

$$x_t = \sum_{j=0}^{J} \frac{1}{j!} \prod_{l=1}^{j} \sum_{i_l=0}^{\infty} \left(\sum_{n=0}^{J-j} \frac{1}{n!} x_{\sigma^n i_1 i_2 \dots i_j} \sigma^n \right) (e_{t-i_1} \otimes e_{t-i_2} \otimes e_{t-i_3} \dots). \tag{34}$$

This Volterra series directly maps the exogenous innovations to the endogenous variables. As noted by Schmitt-Grohe and Uribe (2004), with a first order approximation, shocks only enter with their first moments. The first moments of future shocks in turn drop out when taking expectations of the linearized equations. This determines the property of certainty equivalence, i.e. agents completely disregard of the uncertainty associated with $\mathbb{E}_t[e_{t+1}]$. This property makes the first order approximation not suitable for the analysis of second moment shocks. In a second order approximation there are effects of volatility shocks that enter as cross-products with the other state variables (Fernandez-Villaverde et al. (2011)). This order of approximation is therefore not sufficient to isolate the effects of uncertainty from those of the level shock. As we are interested in analyzing the effects of uncertainty shocks, keeping the the first moment shocks shut off, it is necessary to approximate (33) up to a third order:

$$x_t = \bar{x} + \frac{1}{2} y_{\sigma^2} + \frac{1}{2} \sum_{i=0}^{\infty} (x_i + x_{\sigma^2,i}) e_{t-i} + \frac{1}{2} \sum_{j=0}^{\infty} \sum_{i=0}^{\infty} x_{j,i} (e_{t-j} \otimes e_{t-i})$$
$$+ \frac{1}{6} \sum_{k=0}^{\infty} \sum_{j=0}^{\infty} \sum_{i=0}^{\infty} x_{k,j,i} (e_{t-k} \otimes e_{t-j} \otimes e_{t-i}). \quad (35)$$

A common problem when simulating time series with higher-order approximated solutions is that it often leads to explosive paths for x_t. A common solution, suggested by Kim et al. (2008), is that of "pruning" out the unstable higher-order terms. Nevertheless with the algorithm we have adopted (Lan and Meyer-Gohde (2013)) the stability from the first order solution is passed on to all higher order recursions, and no pruning is hence required.

5.2 Calibration

We calibrate the benchmark model on a quarterly basis for the euro area and set the parameter values according to stylized facts and to previous findings in the literature. The calibrated structural parameters of the model are illustrated in table (1). The discount factor for households is set to 0.9943 which results into a steady state interest rate on deposits of approximately 2 percent, while we set the loan rate for entrepreneurs to 0.975 as in Iacoviello and Neri (2010). The inverse of the Frisch labor supply elasticity is set to 1.0, in line with Christiano et al. (2010). We set the depreciation rate of capital δ to 0.025 and the share of capital in the production process α to 0.25. In the goods market we assume a markup of 20 percent and set ϵ^y to 6, a value frequently used in the literature. According to the posterior estimates of Gerali et al. (2010), we calibrate the paramater for the investment adjustment costs κ_i to 10.2 and the one for the price adjustment costs κ_p to 30.

Regarding the parameters for the banking sector, we base our calibration on Gerali et al. (2010). We set the loan-to-value ratio for entrepreneurs m to 0.35, the elasticities of substitution of the deposit (loan) rate to -1.46 (3.12) which implies a markdown (markup) on the deposit (loan) rate of about 1.6 (2.0) percentage points, values that are in line with statistical evidence of interest rate spreads in the euro area. In addition, bank management costs δ^b are set to 0.0105. Banks retain half of their profits in order to cover bank management costs. For this reason we set φ equal to 0.5. Furthermore, we set the loan rate adjustment costs κ_b to 9.5 and the deposit rate adjustment costs κ_d to 3.5, consistent with the estimation results of Gerali et al. (2010).

We assume the central bank to react aggressively to inflation by setting the parameter ϕ_π to 2.0, while it responds only marginally to changes in output growth ($\phi_y = 0.3$). Additionally, we include interest rate smoothing with a smoothing parameter ρ_r equal to 0.75.

The uncertainty shock to TFP is calibrated according to the empirical evidence in the euro area. We set the volatility of the second moment TFP shock η_z to 15 percent, which is in line with the implied volatility index VSTOXX. The other parameters related to the shock processes are calibrated similarly to Basu and Bundick (2011). The persistence parameters of the first moment TFP shock ρ_z is equal to 0.9. The persistence parameter of the second moment shock ρ_{σ^z} is equal to 0.83.

Table 1: *Deep parameters of the benchmark model*

Parameter	Value	Description
Non-financial sector		
β_h	0.9943	Discount factor private households (savers)
β_e	0.975	Discount factor entrepreneurs (borrowers)
ϕ	1	Inverse of Frisch labor supply elasticity
δ	0.025	Depreciation rate of physical capital
α	0.25	Weight of capital in aggregate production function
ϵ^y	6	Elasticity of substitution in the goods market
κ_i	10.2	Investment adjustment costs
κ_p	30	Price adjustment costs (Rotemberg)
m	0.35	Loan-to-value (LTV) ratio for the entrepreneurs
Financial sector		
ϵ^d	-1.46	Elasticity of substitution for deposits
ϵ^b	3.12	Elasticity of substitution for loans
φ	0.5	Share of banks' retained earnings
δ^b	0.1	Bank management costs
κ_b	9.5	Loan rate adjustment costs
κ_d	3.5	Deposit rate adjustment costs
Monetary Policy		
ϕ^y	0.30	Weight on output in Taylor rule
ϕ^π	2.0	Weight on inflation in Taylor rule
ρ^r	0.75	Interest rate smoothing parameter
Shocks		
z	1	Steady state of TFP
σ^z	0.01	Steady state volatility of TFP first moment shock
ρ_z	0.9	Persistence parameter of TFP first moment shock
ρ_{σ^z}	0.83	Persistence parameter of TFP second moment shock
η_z	0.0015	Volatility of TFP second moment shock

5.3 Results

In the following we analyze the effects of an uncertainty shock to TFP on main macroeconomic aggregates using impulse response functions. The aim is to assess the importance of financial frictions and financial intermediation in response to increases in uncertainty. Therefore, we compare three different specifications of our model. Starting with our benchmark model which we derived in section 4, we successively switch off the frictions in the banking sector and reduce the model finally to one that closely resembles a standard New Keynesian model.

The benchmark model (henceforth BM) includes a variety of financial frictions, such as borrowing constraints on entrepreneurs, monopolistic competition in the banking sector, and sticky loan and deposit rates. Starting from the BM, we switch off the stickiness of loan and deposit rates, such that the retail rates immediately respond to changes in the policy rate. However, we keep monopolistic competition in the banking sector such that there still is a markdown to the deposit rate and a markup to the loan rate. We denote this model as the flexible rate model (FRM). Finally, we switch off the entire banking sector and the borrowing constraints of the entrepreneurs. This model specification comes closest to a standard New Keynesian model which does not include any financial frictions. We refer to this model as Quasi New Keynesian model.[6]

5.3.1 TFP uncertainty

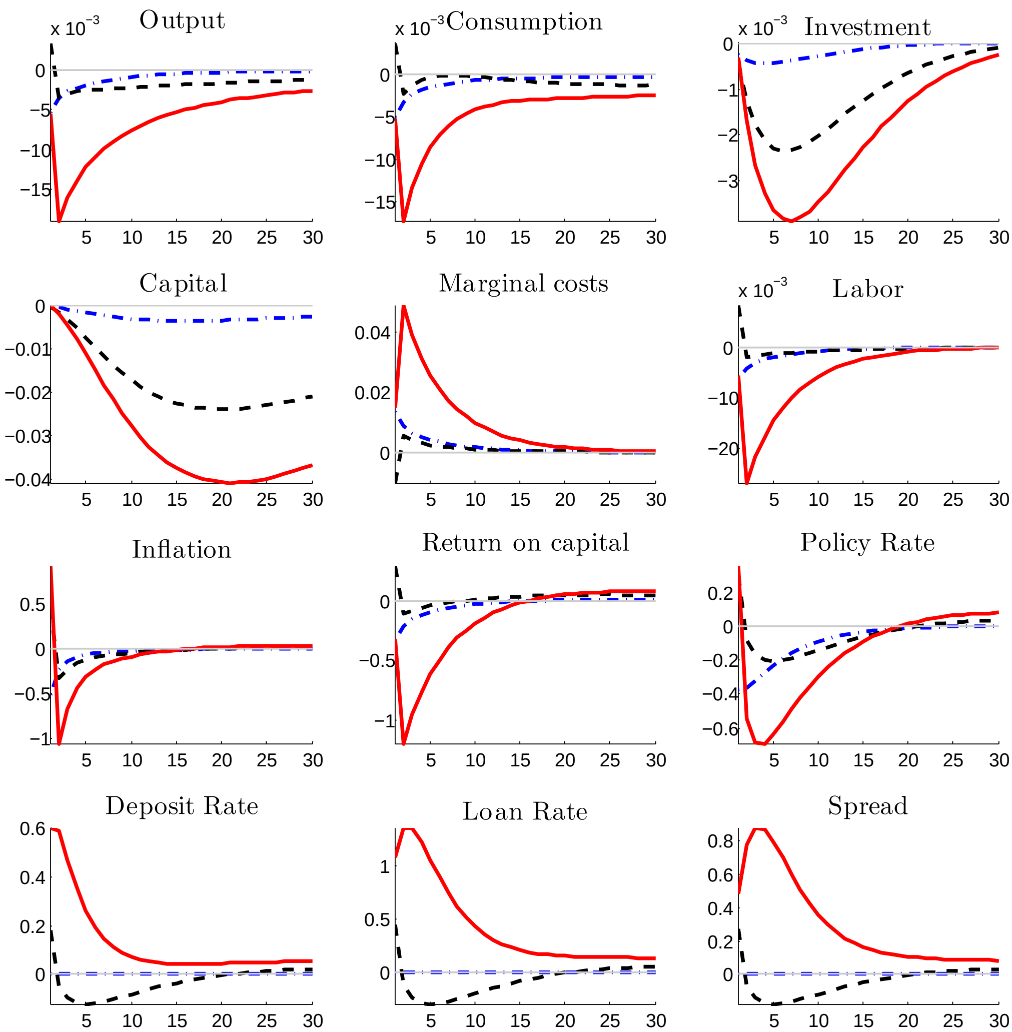
Figure 4 plots the impulse response functions of a one-standard deviation shock to TFP uncertainty for all three models. We consider the Quasi New Keynesian model (blue dashed-dotted line); the Flexible Rate model (black dashed line); and the benchmark model featuring all financial frictions (red solid line). Consistently with the literature, we find that a one-standard deviation increase in TFP uncertainty has dampening effects on macroeconomic aggregates. As in Basu and Bundick (2011) we find that output, consumption and investment co-move negatively under sticky prices, while this is generally not the case under flexible prices.[7] When prices do not immediately adjust to changing marginal costs, the

[6] We call the model Quasi New Keynesian since it has the main characteristics of a NKM but additionally incorporates heterogenous agents.

[7] Under flexible prices, agents reduce consumption due to precautionary motives while they increase their labor supply which boosts output; in a closed economy this leads to an increase

increase in markups of the final good firms leads to a fall in the demand for the intermediate good. This in turn determines the intermediate good firm to reduce their labor input. Hence, aggregate output falls and so does investment. This effect can be seen in the impulse responses of the QNKM.

Figure 4: *Impulse responses to a shock in TFP uncertainty*



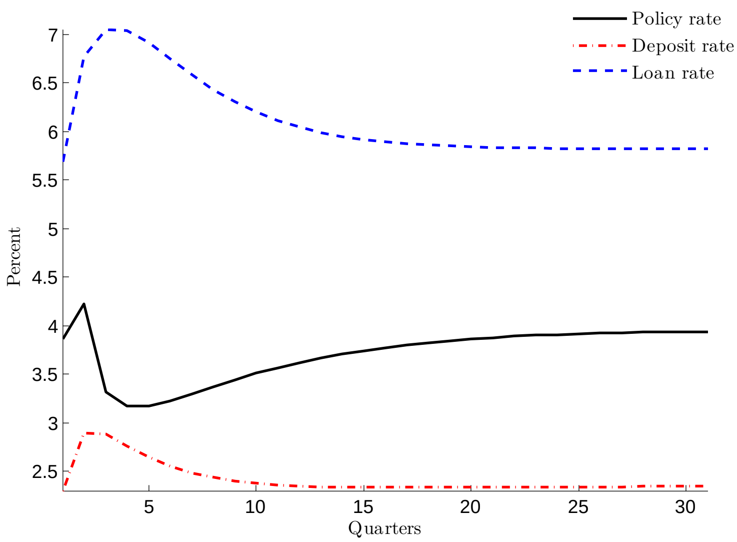
Notes: Red solid line: Benchmark model (BM); Black dashed line: Model with flexible rates (FRM); Blue dashed-dotted line: Quasi New Keynesian model (QNKM). All variables are expressed in percentage deviations from steady state, except interest rates which are expressed in annualized absolute deviations from steady state in basis points and the inflation rate which is expressed as the annualized absolute deviation from steady state in percentage points.

The negative shock is partly offset by the central bank by reducing the nominal

in investment.

interest rate. This becomes more evident when we compare the QNKM and the FRM to the BM. Including a frictional banking sector with sticky retail rates reduces the effectiveness of the transmission mechanism of monetary policy. Due to an increase in TFP uncertainty, which can be interpreted as a higher dispersion future costs for the intermediate firm, marginal costs increase on impact and so does inflation. The central bank responds initially with an increase in the policy rate which leads the loan and deposit to rise. As the effect on marginal costs gets weaker after one quarter, inflation drops and the central bank lowers the interest rate. However, the loan and deposit rate, which are directly relevant for the non-financial sector in the BM, do not immediately follow the change in the policy rate, but slowly adjust to it as they are assumed to be sticky (Figure 5).

Figure 5: *Response of policy and retail interest rates to an uncertainty shock*



Notes: The illustrated scenario is a response to a 150 percent shock in TFP uncertainty.

In the FRM retail rates immediately respond to the change in the policy rate and for this reason the uncertainty shock is not amplified compared to the QNKM.

The result of including a frictional financial sector is that macroeconomic aggregates react stronger to the TFP uncertainty shock. Output and consumption fall about three times as strong as in the QNKM and investment about four times. However, the overall effects of TFP uncertainty are small. This result is consistent with previous studies, such as Born and Pfeifer (2011), Bachmann and Bayer (2011), and Basu and Bundick (2011). This is basically because of two effects. First, the parameter of the Frisch labor supply elasticity is set to a value that is relatively low such that household immediately react to shock and adjust their labor supply. Second, the aggressive and quick response of the central bank to offset the negative shock mitigates the potential effects of uncertainty. The small effects become even more evident when comparing the effects of the uncertainty shock to a shock in the level of TFP. While output only declines 0.02 percent after a standard deviation TFP uncertainty shock it declines by about 1 percent after a negative standard deviation TFP level shock (see Figure A1 in the appendix).

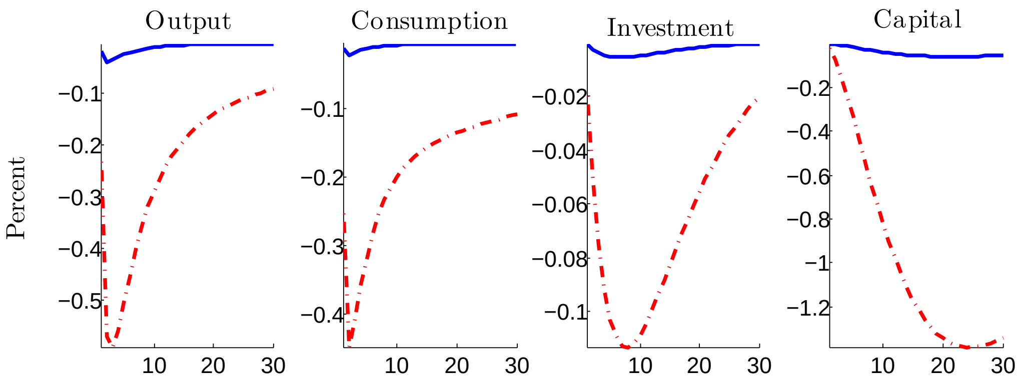
The outcomes of our model are qualitatively in line with the empirical findings in section 2.2. However, the magnitude of the responses of macroeconomic aggregate in the data indicates that uncertainty shocks have a stronger effect in the euro area than predicted by our model.

5.4 Reconciling the model with the data

One possible explanation for the strong effects of uncertainty from the BVAR is that the global financial crisis is included in our data sample. During 2007-2009 uncertainty increased sharply and macroeconomic aggregates plummeted strongly. Empirical analysis from other studies indicate that non-linearities are an important driver to explain the strong amplification of financial markets shocks on the economy. While there tend to be small effects of uncertainty and financial shocks in a "normal" macroeconomic environment, the effects of uncertainty are high in a distressed regime (van Roye (2013), Aboura and van Roye (2013) and Hubrich and Tetlow (2012)). In this subsection we show that in periods of recession, the impact of uncertainty of shocks on economic fluctuations is considerably higher and closer to the empirical findings.

To simulate a distressed scenario, we simultaneously hit the economy with a negative two standard deviations TFP level shock and one standard deviation uncertainty shock. Afterward, we subtract the effect of the TFP shock from that of the combined shock. The outcome is the isolated effect of the uncertainty shock. Figure 6 shows the different impact of the uncertainty shock on main macroeconomic aggregates under two scenarios: the baseline case, as in figure 4, and in times of strong economic downturn, as described above.

Figure 6: *Impulse responses to an uncertainty shock in a normal regime and in distressed regime.*



Notes: The blue solid line represents the IRF to an uncertainty shock in the baseline case; the red dashed-dotted line represents the IRF to an uncertainty shock during a strong economic downturn.

The effects of the uncertainty shocks are significantly stronger in the distressed scenario. This exercise emphasizes the importance of non-linearities and potential regime dependencies, when analyzing uncertainty shocks.

6 Conclusion

In this chapter we present a framework to analyze the impact of uncertainty shocks on macroeconomic aggregates under financial frictions. In particular, we include a banking sector that operates in a monopolistically competitive environment and sticky retail rates in a DSGE model with heterogenous agents. We depart from the strand of literature that analyzes uncertainty shocks under financial frictions on the credit demand side by focusing on frictions on the credit supply side. This seems to be a very important channel through which uncertainty shocks transmit to the real economy. In fact, we show that these features amplify significantly the effects of uncertainty shocks. This finding is mainly due to a reduction in the effectiveness in the transmission mechanism of monetary policy. A possible extension of our analysis could be to include uncertainty in the financial sector. Moreover, a regime-switching DSGE model could be an appropriate extension to shed light on non-linear effects of uncertainty shocks. We leave both to future research.

A Appendix

A.1 Complete model equations

A.1.1 First order conditions of the households

Households' Euler equation

$$\frac{1}{c_t^h} = \beta \mathbb{E}_t \left[\frac{1}{c_{t+1}^h} \frac{(1 + r_t^d)}{(1 + \pi_{t+1})} \right], \tag{36}$$

Labor supply equation

$$l_t^\phi = w_t \frac{1}{c_t^h}, \tag{37}$$

Households' budget constraint

$$c_t^h + d_t = w_t l_t + (1 + r_{t-1}^d) \frac{d_{t-1}}{(1 + \pi_t)} + J_t^R, \tag{38}$$

A.1.2 First order conditions entrepreneurs

$$s_t \bar{m} \mathbb{E}_t (1 + \pi_{t+1})(1 - \delta^k) + \beta^e \mathbb{E}_t \left[\left(\frac{1}{c_{t+1}^e} \right) \left((1 - \delta^k) + r_{t+1}^k \right) \right] = \frac{1}{c_t^e}, \tag{39}$$

Wage equation

$$w_t = (1 - \alpha) \frac{y_t^e}{l_t x_t}, \tag{40}$$

Euler equation entrepreneurs

$$\frac{1}{c_t^e} - s_t (1 + r_t^b) = \beta^e \mathbb{E}_t \left[\frac{1}{c_{t+1}^e} \frac{(1 + r_t^b)}{(1 + \pi_{t+1})} \right], \tag{41}$$

Budget constraint entrepreneurs

$$c_t^e + \left(\frac{(1 + r_{t-1}^b) b_{t-1}}{1 + \pi_t} \right) + w_t l_t + q_t^k k_t = \frac{y_t^e}{x_t} + b_t + q_t^k (1 - \delta) k_{t-1}, \tag{42}$$

Production function

$$y_t^e = z_t \left(k_{t-1} \right)^\alpha l_t^{1-\alpha}, \tag{43}$$

Borrowing constraint

$$(1+r_t^b)b_t = m\mathbb{E}_t\Big[q_{t+1}^k(1+\pi_{t+1})k_t(1-\delta)\Big], \tag{44}$$

A.1.3 Capital producers

Return on capital

$$r_t^k = \frac{\alpha a_t \left(k_{t-1}\right)^{\alpha-1} l_t^{1-\alpha}}{x_t}, \tag{45}$$

Capital equation

$$k_t = (1-\delta)k_{t-1} + \left[1 - \frac{\kappa_i}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2\right] i_t, \tag{46}$$

A.1.4 Banks

$$R_t^b = R_t^d = r_t, \tag{47}$$

$$k_t^b(1+\pi_t) = (1-\delta^b)k_{t-1}^b + \varphi J_{t-1}^b, \tag{48}$$

$$b_t = d_t + k_t^b, \tag{49}$$

A.1.5 Markup and markdown equations

Markdown on deposits

$$\begin{aligned} &-1 + \frac{\epsilon_t^d}{(\epsilon_t^d - 1)} - \frac{\epsilon_t^d}{(\epsilon_t^d - 1)}\frac{r_t}{r_t^d} - \kappa_d\left(\frac{r_t^d}{r_{t-1}^d} - 1\right)\frac{r_t^d}{r_{t-1}^d} \\ &+ \beta_h\mathbb{E}_t\left[\frac{c_t^h}{c_{t+1}^h}\kappa_d\left(\frac{r_{t+1}^d}{r_t^d} - 1\right)\left(\frac{r_{t+1}^d}{r_t^d}\right)^2\frac{d_{t+1}}{d_t}\right] = 0, \end{aligned} \tag{50}$$

Markup on loans

$$1 - \frac{\epsilon^b}{(\epsilon^b - 1)} + \frac{\epsilon^b}{(\epsilon^b - 1)} \frac{R_t^b}{r_t^b} - \kappa_b \left(\frac{r_t^b}{r_{t-1}^b} - 1 \right) \frac{r_t^b}{r_{t-1}^b} + \beta_h \mathbb{E}_t \left[\frac{c_t^h}{c_{t+1}^h} \kappa_b \left(\frac{r_{t+1}^b}{r_t^b} - 1 \right) \left(\frac{r_{t+1}^b}{r_t^b} \right)^2 \frac{b_{t+1}^E}{b_t} \right] = 0, \tag{51}$$

Bank profits

$$J_t^b = r_t^b b_t - r_t^d d_t - \frac{\kappa_d}{2} \left(\frac{r_t^d}{r_{t-1}^d} - 1 \right)^2 r_t^d d_t - \frac{\kappa_b}{2} \left(\frac{r_t^b}{r_{t-1}^b} - 1 \right)^2 r_t^b b_t, \tag{52}$$

A.1.6 Retailers

$$J_t^R = y_t \left(1 - \frac{1}{x_t} - \frac{\kappa_p}{2} \pi_t^2 \right), \tag{53}$$

Nonlinear Phillips curve

$$1 - \epsilon_t^y + \frac{\epsilon_t^y}{x_t} - \kappa_p \pi_t (1 + \pi_t) + \beta_h \mathbb{E}_t \left[\frac{c_t^h}{c_{t+1}^h} \kappa_p \pi_{t+1} (1 + \pi_{t+1}) \frac{y_{t+1}}{y_t} \right] = 0, \tag{54}$$

A.1.7 Aggregation and Equilibrium

$$c_t = c_t^h + c_t^e, \tag{55}$$

$$y_t = c_t + [k_t - (1 - \delta) k_{t-1}] + \delta^b \frac{k_{t-1}^b}{\pi_t} + ADJ_t, \tag{56}$$

A.1.8 Taylor Rule and Profits CB

$$\frac{1 + r_t}{1 + r} = \left(\frac{1 + r_{t-1}}{1 + r} \right)^{\phi_r} \left[\left(\frac{1 + \pi_t}{1 + \pi} \right)^{\phi_\pi} \left(\frac{y_t}{y_{t-1}} \right)^{\phi_y} \right]^{(1 - \phi_r)}, \tag{57}$$

A.1.9 Exogenous Processes

TFP level shock

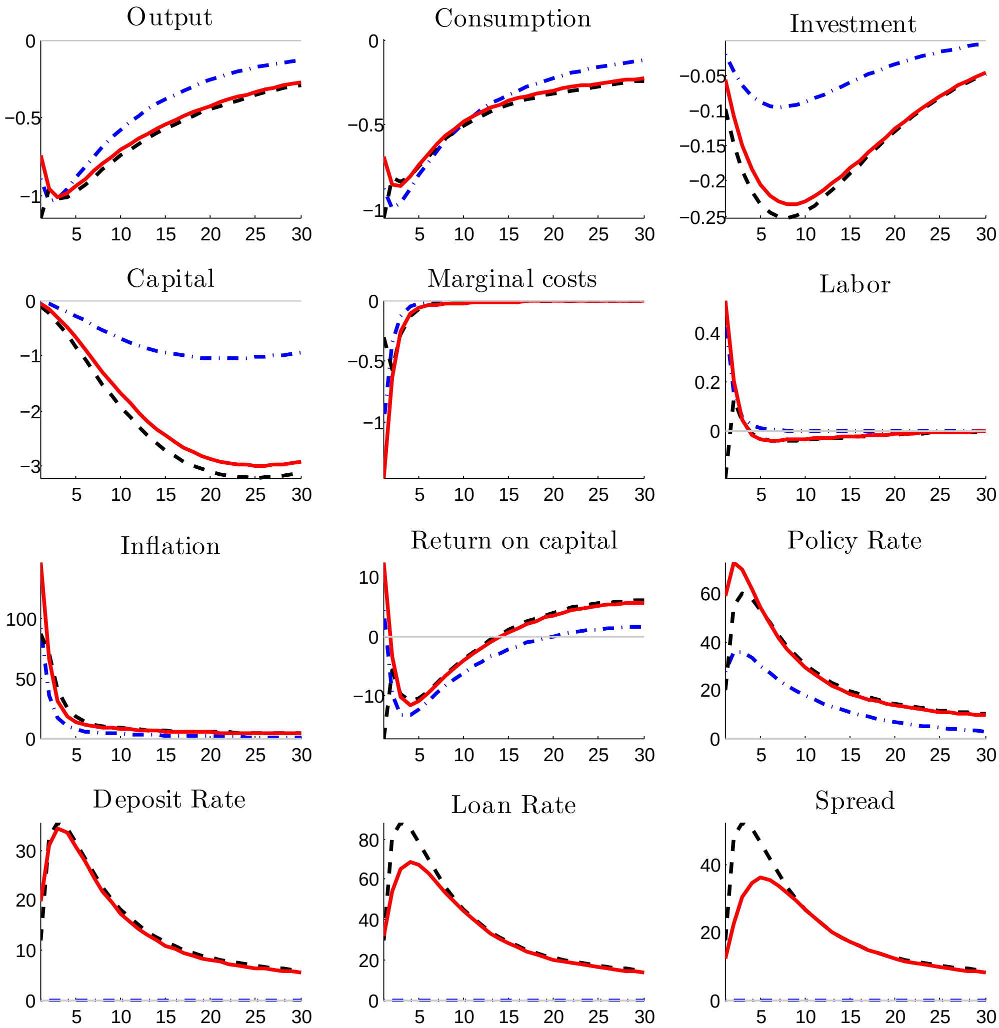
$$z_t = (1 - \rho_z)z + \rho_z z_{t-1} + \sigma_t^z e_t^z, \tag{58}$$

TFP uncertainty shock

$$\sigma_t^z = (1 - \rho_{\sigma^z})\sigma^z + \rho_{\sigma^z}\sigma_{t-1}^z + \eta_z e_t^{\sigma_z}, \quad \text{where } e_t^{\sigma_z} \sim \mathcal{N}(0,1) \tag{59}$$

A.2 Impulse responses to level shocks

Figure A1: *Impulse response functions to a shock in the level of TFP*



Notes: Red solid line: Benchmark model (BM); Black dashed line: Model with flexible rates (FRM); Blue dashed-dotted line: Quasi New Keynesian model (QNKM). All variables are expressed in percentage deviations from steady state, except interest rates which are expressed in annualized absolute deviations from steady state in basis points and the inflation rate which is expressed as the annualized absolute deviation from steady state in percentage points.

A.3 Details on data used in estimation

Below we describe the data we use in the empirical exercise in section 3.

Uncertainty index We use both the implied volatility index VSTOXX provided by Thomson Financial Datastream and the the Eurostoxx50 which we use to approximate a historical volatility index prior to 1999. For this proxy we use a standard GARCH(1,1) model using monthly data and build 3-month averages over this index. Source: Thomson Financial Datastream.

Real GDP We use the time series YER provided by the AWM database originally provided by Fagan et al. (2001) and take log-differences of this index. For data after 2011Q4 we use the log-differences of the real GDP index provided by Eurostat. Source: AWM database and Eurostat.

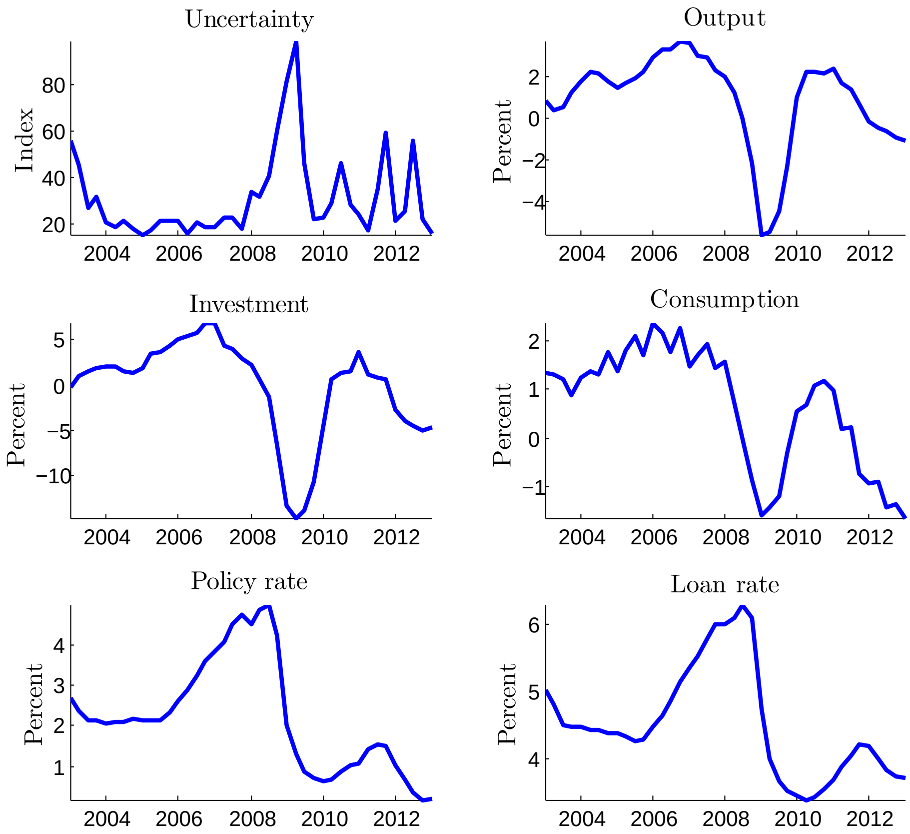
Investment We use the time series ITR provided by the AWM database originally provided by Fagan et al. (2001) and take log-differences of this index. For data after 2011Q4 we use the log-differences of the real GDP index provided by Eurostat. Source: AWM database and Eurostat.

Consumption We use the time series PCR provided by the AWM database originally provided by Fagan et al. (2001) and take log-differences of this index. For data after 2011Q4 we use the log-differences of the real GDP index provided by Eurostat. Source: AWM database and Eurostat.

Loan rate Interest rate charged by monetary financial institutions (excluding Eurosystem) for loans to non-financial corporations (outstanding amounts, all maturities), in percent (ECB). Source: ECB and Thomson financial datastream (Code: EMBANKLPB).

Interest rate We use the 3-month average of the unsecured Euro interbank offered rate (Euribor). Source: Thomson Financial Datastream (Code: EMINTER3)

Figure A2: *Variables used in estimation*



Notes: The uncertainty variable is the VSTOXX. All variables are expressed in log-differences, except the policy rate and the loan rate which are expressed in levels. estimated median impulse responses.

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