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Are You a Lehman, Brother? Interbank Uncertainty in a DSGE Model

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Interbank Uncertainty and Business Cycle Transmission

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PRELIMINARY DRAFT

Abstract

Using a RBC framework, we show that uncertainty induces adverse real effects under flexible prices and standard preferences if transmitted through the interbank market. However, macro uncertainty about total factor productivity does not. Interbank uncertainty is modeled as exogenous change in the dispersion of beliefs about the fraction of interbank loans expected to be repaid. In our model higher uncertainty in wholesale banking leads to reductions in interbank lending activities as banks become more funding constraint. This induces a deleveraging process which reduces loans to firms and investment.

Keywords: uncertainty shock, interbank market, financial frictions, counterparty risk

JEL: E170, E320, E370

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1 Introduction

When news about incalculable risks in the market for subprime mortgage hit the headlines in September 2007, interbank lending activity responded dramatically. Measures of financial stress, like the spread between LIBOR and the Overnight Index Swap (OIS) jumped up sharply (see left panel of Figure 1).¹ [Taylor and Williams \(2009\)](#), among others, argue that increases in counterparty risk contributed substantially to these movements. This is supported by the tight link between the LIBOR–OIS spread and the LIBOR–Repo spread.² Especially during the two most incisive events, the outbreak of the subprime crisis (*I*) and the collapse of Lehman Brothers (*II*), the wedge between the two spreads was virtually zero. In the wake of both these events banks became increasingly uncertain about the solvency of their counterparties fearing that the collapse of a peer institution might deteriorate their own solvency. This put interbank lending under stress (see the right panel of Figure 1). At the onset of the subprime crisis interbank lending first slowed and then came to a full stop, dropping from a total of about \$400 bn in September 2007 to only \$100 bn in December 2013.

The dramatic effects of the subprime and ensuing financial crisis are well documented.³ Empirical evidence suggests that uncertainty, in general, might have been a major contributor (see for example [Stock and Watson, forthcoming](#)). But to what degree did interbank uncertainty play a role in triggering these events?⁴ Can an amplified risk perception in the interbank market affect interbank lending activity strongly enough to explain substantial decreases in real growth that we observed in the US? These are pressing questions for both politicians and regulators as their answers might help to prevent further financial meltdowns of the magnitude we experienced from 2008 to 2012. However, the explicit modeling of uncertainty in the market for inter-bank lending has so far been neglected in the literature.

In this paper we introduce inter-bank market uncertainty into an RBC setup to model the effects of a sudden increase in counterparty risk onto financial markets and the real economy. We build upon a standard RBC model with heterogeneous agents augmented by a market for financial intermediation. Heterogeneous banks finance loans with household deposits, interbank lending and equity. Following [Gertler and Kiyotaki \(2011\)](#) we introduce an agency problem into the interbank market to impose

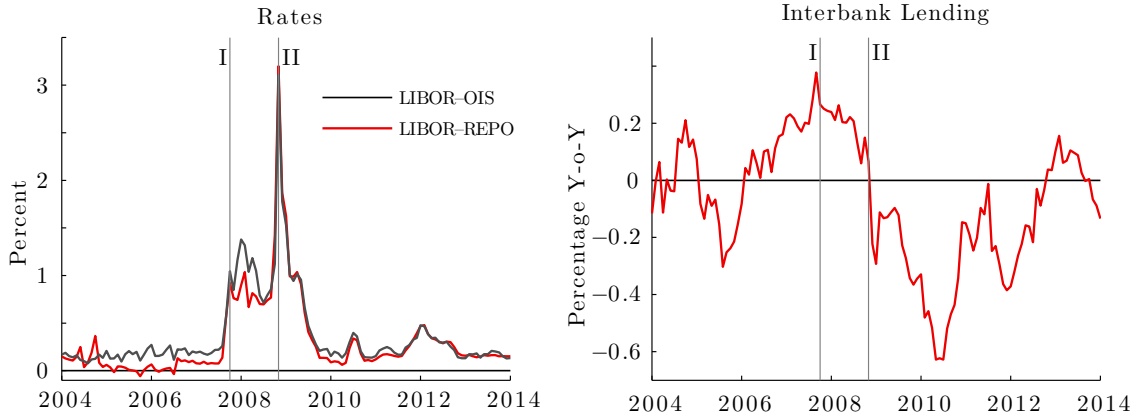
¹Subtracting OIS from LIBOR controls for effects on LIBOR that are due to changes in expectations about the future path of the federal funds rate. Explanations for the remaining difference are e.g. liquidity needs or counterparty risk.

²The LIBOR-Repo spread is a spread between unsecured and secured interbank loans and therefore a measure of counterparty risk.

³See for example [Reinhart and Rogoff \(2009\)](#) and [Campello, Graham, and Harvey \(2010\)](#) among others.

⁴Throughout this paper we use the terms counterparty risk and interbank uncertainty interchangeably.

Figure 1: Interbank Risk



Notes: LIBOR–OIS denotes the spread between the 3-month LIBOR and the 3-month Overnight Index Swap. LIBOR–REPO denotes the spread between 3-month LIBOR and the interest rate on 3-month repurchase agreements on treasuries between banks. *I* marks September 2007, the beginning of the subprime crisis and *II* marks October 2008, the collapse of Lehman Brothers.

a liquidity constraint on financial intermediaries: we assume that borrowing banks in the interbank market can divert a fraction of their total assets. Thus, banks with excess liquidity demand are only able to acquire funds from both the interbank and the deposit market if creditors anticipate that there is no incentive to divert the funding. As a novel feature of our model we introduce uncertainty in the interbank market. When banks give loans to one another they have a probability distribution over the fraction they expect to be repaid. We define interbank uncertainty as the dispersion of this probability distribution, which is time-varying. This setup allows us to interpret the dispersion as uncertainty banks attach to the degree of the interbank market frictions.

A frictional market for interbank liquidity introduces a novel transmission mechanism through which uncertainty can affect financial market performance and real activity. Generating business cycle co-movement does thereby not depend on a sticky price environment and non-separable utility as in models without financial market (Basu and Bundick, 2012; Cesa-Bianchi and Fernandez-Corugedo, 2013). In our model an increase in uncertainty raises doubts about the fraction of interbank loans to be repaid. This increases interbank lending rates and reduces interbank lending activities. Banks in need for interbank funding become liquidity constraint and must deleverage. Loan supply to the real economy, investment and production decrease, depressing the equity value of entrepreneurs. Since banks are the holder of this equity, they will suffer losses on their assets and, through the interbank market friction, will become even more liquidity constraint. Thus, increasing uncertainty triggers a vicious cycle of deteriorating banks' equity, deleveraging and decreasing liquidity supply.

In contrast, standard macro (TFP) uncertainty (see for example [Cesa-Bianchi and Fernandez-Corugedo, 2013](#)) is not able to generate business cycle correlations in our model. The reason is straightforward: our model features standard separable preferences and fully flexible prices with the only friction occurring within the interbank market. Therefore we have muted all toeholds for uncertainty usually employed in the literature. We do not claim that macro uncertainty accompanied with stick prices don't play an important role in explaining real effects of uncertainty. We instead think that interbank market frictions offer an additional important toehold for uncertainty which does not rely sticky prices to generate plausible business cycle movements.

We calibrate the model for the US economy at the onset of the financial crises. We show that with fully flexible prices and interbank market uncertainty being the only friction our model is able to explain an economic significant fraction of real slack experienced after increases in counterparty risk perception.

Our paper is complementary to the research on uncertainty and its consequences for economic activity, which has found renewed interest starting with [Bloom \(2009\)](#). A strand of this literature links uncertainty with financial frictions. These models allow uncertainty to operate via the standard "financial accelerator" (e.g., [Dorofeenko, Lee, and Salyer, 2008](#); [Christiano, Motto, and Rostagno, Forthcoming](#); [Arellano, Bai, and Kehoe, 2012](#); [Chugh, 2012](#); [Cesa-Bianchi and Fernandez-Corugedo, 2013](#); [Gilchrist, Sim, and Zakrajsek, 2013](#)). In these papers uncertainty is either modeled as the volatility of total factor productivity (macro uncertainty) or as dispersion in firms' idiosyncratic productivity (micro uncertainty). On the one hand these models share the common feature that uncertainty only exists with respect to the default probability of firms' loans. Our paper extends the scope of uncertainty also to the supply side of credit and the interbank market and shows that counterparty risk perception has economic significant effects. On the other hand these model either rely on a sticky price setup or generate negative correlation between consumption and investment. Our model is able to generate sensible business cycle dynamics in a flexible price environment.

The remainder of this paper is structured as follows. The next section lays out the intuition for the effects of uncertainty. Section 3.8 describes our model. Section 4 discusses calibration. Section 5 shows simulation results and Section 6 concludes.

2 Intuition

3 Model

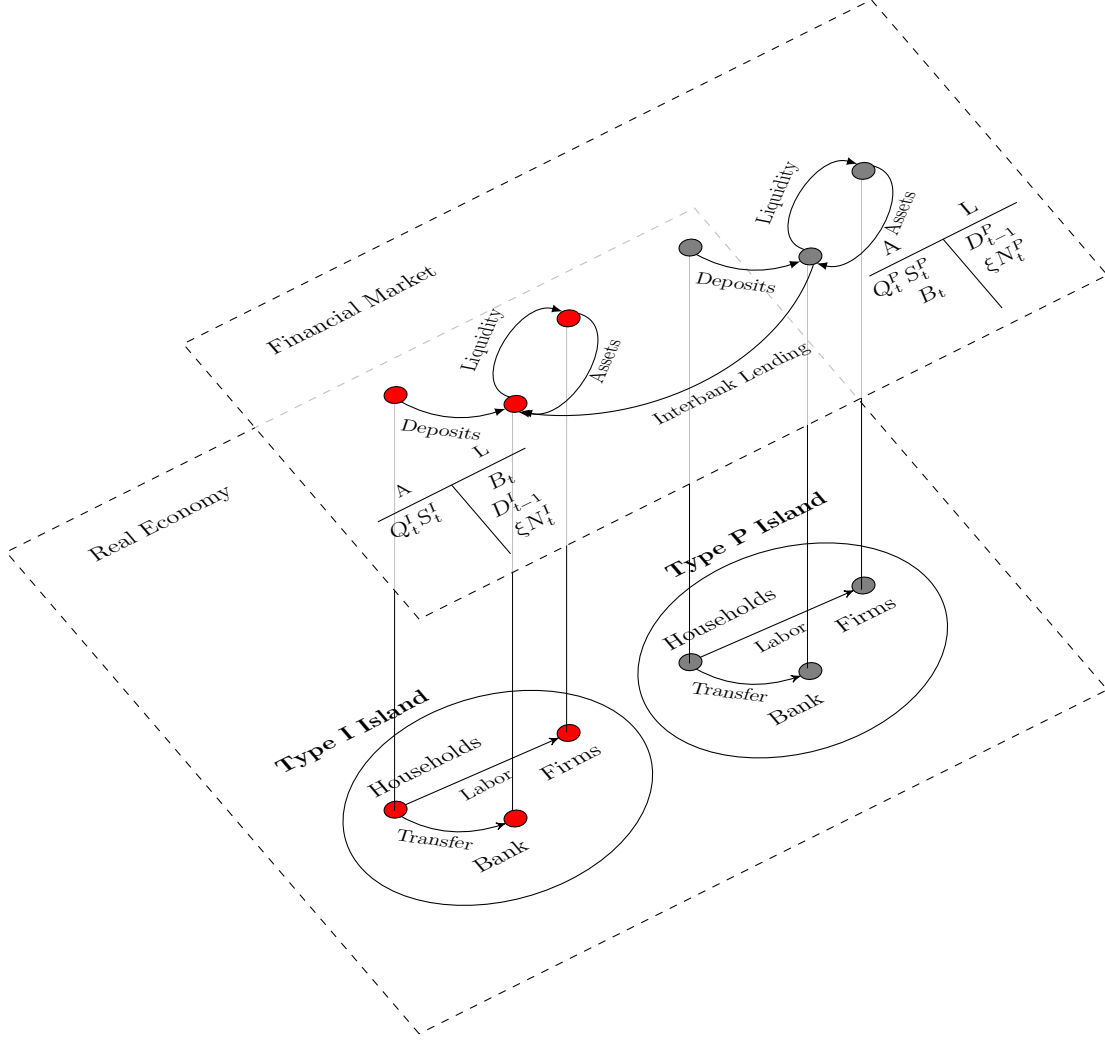
To add a toehold for interbank market uncertainty to an otherwise standard RBC model we draw upon the framework of [Gertler and Kiyotaki \(2011\)](#). However, their

model is primarily one of real interest rate spreads where the distinction between the deposit and the interbank market is not crucial for the results. Therefore, to add an active role for interbank lending activity to the model we introduce –in the spirit of [Dib \(2010\)](#)– structural heterogeneity to banks. We assume that there is a continuum of islands $h \in [0, 1]$, each inhabited by a representative household, a representative firm and a representative bank. Islands are heterogeneous in the sense that a share ι is inhabited by patient households with discount factor β_P and a share $1 - \iota$ is inhabited by impatient households with discount factor β_I and $\beta_I < \beta_P$. We refer to the former type as islands P and to the latter as type I islands. Since the household on island h owns the representative bank h , banks that are owned by patient households are assumed to act as creditors in the interbank market as they face a high deposit supply. In contrast, banks owned by an impatient household are assumed to act as counterparties for banks P , as they face a low deposit supply. Type I banks are less efficient in raising deposits and have to pay constant lump-sum effort costs Γ . We introduce this reduced form steady state deposit market friction to ensure positive steady state interbank liquidity flows between type P and type I islands. Γ creates a wedge between steady state deposit supply and loan demand on type I of islands. This wedge is only closed through interbank market lending.⁵ This setup allows us to introduce an increase in interbank market uncertainty in a straightforward manner: we start in a situation in which the interbank market functions smoothly, that is type P banks provide interbank liquidity to type I banks. We then consider a sudden and unexpected increase in counterparty risk.⁶ Figure 2 summarizes our general framework and shows the most important interactions between agents.

⁵In contrast, in [Gertler and Kiyotaki \(2011\)](#) there are no steady state interbank liquidity flows. To generate interbank flows off steady state they assume that deposits are fixed prior to the arrival of investment opportunities. [Dib \(2010\)](#) assumes that banks which act as borrowers in the interbank market cannot take deposits. Thus, interbank lending is their only source of liquidity. In contrast in our setup both type of banks can tap the local deposit market.

⁶Note that we need structural heterogeneity of banks to be able to consider the second moment uncertainty shock independent of any first moment shocks. For example [Gertler and Kiyotaki \(2011\)](#) activate the interbank market through an iid Markov shock to investment opportunities. Using this setup, our simulation results would include both effects of the investment shock and the uncertainty shock.

Figure 2: General Framework



3.1 Interbank Market friction

The interbank market to be frictional. We follow [Gertler and Kiyotaki \(2011\)](#) and assume that in each period banks that receive interbank market liquidity can divert a fraction of their balance sheet. In particular, bankers can divert total assets $Q_{It}S_{It}$ minus a safe fraction ν of deposits D_{It} and a safe fraction ω_t of interbank funding. If bankers take this road, they liquidate their investment projects and default on their debt such that no interest will be paid and return received. The net value of divertable assets is given by

$$Q_{It}S_{It} - \nu D_{It-1} - \omega_t B_t - \Gamma,$$

where the parameter ν and the stochastic variable ω_t denote the safe fraction of the respective funding source on island I . Γ is a constant and guarantees that deposits and interbank lending are positive in steady state. The possibility to divert assets introduces an incentive constraint for bankers I . They have no incentive to divert

assets if the present expected future payoff of today's lending and funding decisions is larger than the net value of assets divertable, i.e. if

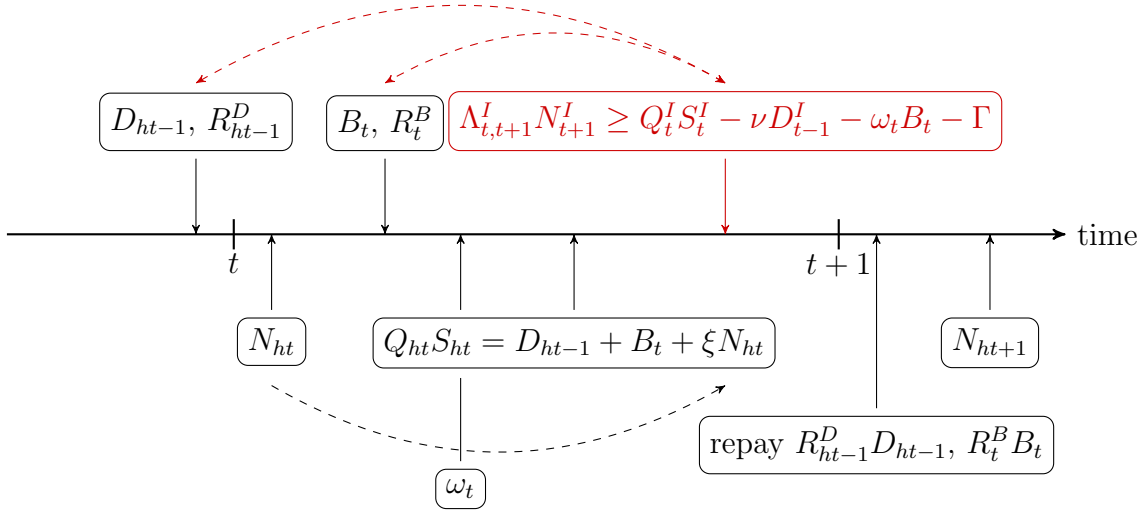
$$\mathbb{E}_t [\Lambda_{t,t+1}^I N_{It+1}] \geq Q_{It} S_{It} - \nu D_{It-1} - \omega_t B_t - \Gamma \quad (3.1)$$

where $\Lambda_{t,t+s}^I$ denotes the pricing kernel of household I . Note, that we assume that each banker lives only for one period before returning to the respective household. Thus, the profits the bank sacrifices when diverting are next period's returns due to today's lending and funding decisions. In that sense the banker is myopic as she does not internalize any effects beyond her lifetime as banker.

3.2 Timing

Our timing assumption is as follows: at the end of period $t-1$ the deposit market for period t opens on both types of islands. Household and banks agree on the amount of deposits D_{ht-1} and on the interest rate R_{ht-1}^D . Then the deposit market closes. At the beginning of period t the new banker receives start-up transfer ξN_{ht} . Firms decide on their investment decisions and sell equity at price Q_{ht} to the bank. Given the already fixed deposits, D_{It-1} , banks on type I of islands decide how much interbank liquidity they need. The interbank market opens and B_t and R_t^B are decided upon. This determines the liability composition of banks' balance sheets. Banks then lend to firms. This determines the asset side of banks' balance sheets. When providing liquidity to banks of type I , both local depositors and peer institutions of type P internalize the financial market friction. At the beginning of period $t+1$ banks' assets pay off and net worth is determined, fraction ξ of which is transferred to the next banker as startup. Our timing assumption therefore reflects the different natures of banks' funding sources. Since deposits are pre-determined they act as a stable funding source which can not react instantaneously to sudden changes in liquidity demand. In contrast, interbank liquidity is a flexible source to satisfy short-run liquidity demand. Our timing assumption is summarized in Figure 3.

Figure 3: Timing Assumption



3.3 Household

Each island h of either type P and I is inhabited by homogeneous households of mass unity. Each period one household member is appointed to run the island's bank for one period. To set up office the banker is equipped with a start-up transfer from the household and she routes banking profits back to the household.

$$\max_{\{C_{ht}, L_{ht}, D_{ht}\}_{s=0}^{+\infty}} \mathbb{E}_t \left[\sum_{s=0}^{+\infty} \beta_h^s \mathcal{U}(C_{ht+s}, L_{ht+s}) \right]$$

$s.t.$

$$C_{ht} + D_{ht} = w_{ht} L_{ht} + R_{ht-2}^D D_{ht-2} + T_{ht} \quad \forall t,$$

where C_{ht} , L_{ht} , D_{ht} and w_{ht} denote real consumption, working hours supplied, deposits and the real wage rate, respectively. The household owns the final good firm, the capital good producer and the bank and receives profits T_{ht} from these entities in a lump sum fashion. Note that T_{ht} includes profits of periods $t-1$ banker and is net of the start-up transfer to the new banker. Finally, R_{ht}^D denotes the gross interest rate on deposits. Unlike the deposit market on type P of islands, the deposit market on islands I is frictional in the sense that banks can divert a fraction $1 - \nu$ of deposits. Therefore, households on islands I also internalize Equation (3.1) when providing deposits to banks. The optimality conditions for the household are given

by

$$w_{ht} = -\frac{\mathcal{U}'_C(C_{ht}, L_{ht})}{\mathcal{U}'_N(C_{ht}, L_{ht})}, \quad h \in \{P, I\} \quad (3.2)$$

$$\mathcal{U}'_C(C_{ht}, L_{ht}) = \beta_P^2 R_{Pt}^D \mathbb{E}_t [\mathcal{U}'_C(C_{Pt+2}, L_{Pt+2})] \quad (3.3)$$

$$\mathcal{U}'_C(C_{It}, L_{It}) = \beta_I R_{It}^D \mathbb{E}_t [\beta_I \mathcal{U}'_C(C_{It+2}, L_{It+2}) + \lambda_{t+1}(\beta_I \nu - \Lambda_{t+1,t+2}^I)] \quad (3.4)$$

where λ_t denotes the Lagrange multiplier on the incentive constraint. Note that for the case that the incentive constraint is not binding Equation (3.4) collapses to Equation (3.3). If $\lambda > 0$ the bank's incentive to divert assets affects current consumption. For $\nu < \mathcal{U}'_C(C_{It+2}, L_{It+2})/\mathcal{U}'_C(C_{It+1}, L_{It+1})$ consumption will be shifted into the present as the marginal utility under diverting ($\nu \mathcal{U}'(C_{It+1}, L_{It+1})$) is lower than the marginal utility if deposits are repaid ($\mathcal{U}'_C(C_{It+2}, L_{It+2})$). The household has thus the incentive to reduce the bank's diverting incentive by reducing deposits.

3.4 Interbank Market

Each period firms invest into new capital and refurbish the old capital stock. To this end they need funds which they obtain by issuing equity to the representative bank on their island. To buy equity banks need liquidity. Banks of type P can only tap the local deposit market, whereas banks of type I can tap both the local deposit market and the interbank market for liquidity. As explained in Section 3.1 the interbank market is frictional.

3.4.1 Type P islands

Each period one member of the representative household on islands P is appointed to run the island's representative bank for one period. That is at the end of period $t - 1$ she decides how many deposits, D_{Pt-1} , to take. After having received the start-up transfer at the beginning of period t she decides how much retail (S_{Pt}) and interbank loans (B_t) to hand out.⁷ After period t ends she becomes part of the household again. In period $t + 1$ the returns and costs of her decisions during periods $t - 1$ and t materialize and she will receive the profits. Then, a new banker is appointed. To set up office at the beginning of each period the banker receives a start-up transfer from the previous period's banker. This transfer is proportional to the beginning of period bank net worth, ξN_{Pt} . It is important to note that each banker does not internalize the amount of start-up transfer she will give to the next banker. This assumption prevents banks from accumulating enough equity over time to overcome borrowing needs. Thereby, ξ is chosen to be small enough such that the bank will require external funding. The balance sheet identity of type P banks

⁷Note that neither B_t nor R_t^B has a subscript h as B_t denotes the equilibrium liquidity flow from islands P to islands I .

thus requires

$$Q_{Pt}S_{Pt} + B_t = D_{Pt-1} + \xi N_{Pt} \quad (3.5)$$

where S_{Pt} is the values of loans funded in period t and Q_{Pt} the market price of entrepreneurs' equity. Loans are given to the final good producer for investment into capital. Each loan is a contingent claim on the payoffs of the new capital unit.

Let R_t^B denote the gross interest rate on interbank loans, R_{Pt}^D the marginal costs of a liquidity unit funded by deposits and $\Lambda_{Pt,t+s}$ the pricing kernel of household P . Then the law of motion for bank's net worth is given by

$$N_{Pt} = [Z_{Pt} + (1 - \delta)Q_{Pt}]S_{Pt-1} + R_{t-1}^B B_{t-1} - R_{Pt-2}^D D_{Pt-2}, \quad (3.6)$$

where Z_{Pt} denotes the productivity return from financing one unit of capital.

Banks maximize expected net worth in the next period. The optimization problem is two-stage. first, at the end of period $t - 1$ the deposit market opens and deposits and deposit rate are determined given expectations of tomorrow's liquidity needs. Second, in period t interbank market conditions and loan supply to the real economy are determined.

$$\max_{\{D_{Pt-1}\}} \mathbb{E}_{t-1} [\Lambda_{t-1,t+1}^P N_{Pt+1}] \quad s.t. \quad (3.1), (3.5), (3.6)$$

with first-order condition

$$\mathbb{E}_{t-1} [\Lambda_{t,t+1}^P] R_{Pt-1}^D = \mathbb{E}_{t-1} [\mu_t^P] \quad (3.7)$$

where μ_t^P denotes the Lagrange multiplier for the balance sheet identity. This equation implies, that the higher the shadow price for a marginal extension of loan providence is expected to be, the higher is the deposit rate as banks deposit demand increases.

In the second stage banks optimize

$$\max_{\{S_{Pt}, B_t\}} \mathbb{E}_t [\Lambda_{t,t+1}^P N_{Pt+1}] \quad s.t. \quad (3.1), (3.5), (3.6)$$

with first order conditions

$$\mu_t^P = \mathbb{E}_t [\Lambda_{t,t+1}^P R_{Pt+1}^K] \quad (3.8)$$

$$\mu_t^P = R_t^B \mathbb{E}_t [\Lambda_{t,t+1}^P - \Lambda_{t,t+1}^I \lambda_t] + \omega_t \lambda_t \quad (3.9)$$

To gain further insights into our model mechanics we can combine Equations (3.7), (3.8) and (3.9) to read

$$\begin{aligned} \mathbb{E}_{t-1} [\Lambda_{t,t+1}^P R_{t-1}^D] &= \mathbb{E}_{t-1} [\Lambda_{t,t+1}^P R_{Pt+1}^L] \\ \mathbb{E}_{t-1} [\Lambda_{t,t+1}^P (R_t^B - R_{Pt-1}^D)] &= \mathbb{E}_{t-1} [\lambda_t (\Lambda_{t,t+1}^I R_t^B - \omega_t)] \end{aligned}$$

with gross return of capital $R_{Pt}^K \equiv (Z_{Pt} + (1-\delta)Q_{Pt})/Q_{Pt-1}$. Since the deposit market is frictionless on islands P the first equations shows that there is no spread between the marginal costs of deposits banks and the marginal return on loan providence. This is not necessarily the case on the interbank market. The second equation relates the spread between the interbank lending rate, R_t^B , and the deposit rate to the shadow value of the incentive constraint, λ_t , and to the interbank friction ω_t . If the incentive constraint does not bind, $\lambda_t = 0$, the two interest rates are equal. If, however, $\lambda_t > 0$ then $R_t^B > R_{Pt-1}^D$. In this case banks of type P would like to extend their interbank lending activities, however, since the incentive constraint is binding, an additional marginal unity of interbank lending would violate the constraint and trigger the diverting of assets which constraints the lending activities and keeps the interbank market rate high.

3.4.2 Type I islands

The setup on type I islands is similar to the one of type P . In addition to being able to divert interbank funding, banks I can also divert deposits. Since type I of islands receive interbank market liquidity their balance sheet identity is given by

$$Q_{It}S_{It} = D_{It} + B_t + \xi N_{It} \quad (3.10)$$

The law of motion for net worth reads

$$N_{It} = [Z_{It} + (1 - \delta)Q_{It}] S_{It-1} - R_{It-1}^D D_{It-2} - R_{t-2}^B B_{t-1} \quad (3.11)$$

The first stage optimization problem on I is given by

$$\max_{\{D_{It-1}\}} \mathbb{E}_{t-1} \left[\Lambda_{t-1,t+1}^I N_{It+1} \right] \quad s.t. \quad (3.1), (3.10), (3.11)$$

The first-order condition is

$$\mathbb{E}_{t-1} \left[(1 + \lambda_t) \Lambda_{t,t+1}^I \right] R_{It-1}^D = \mathbb{E}_{t-1} [\mu_t^I + \nu \lambda_t] \quad (3.12)$$

Note that for $\mathbb{E}_{t-1}[\lambda_t] = 0$ this equation is identical to (3.2), as deposit supply is unaffected by the incentive constraint.

At the beginning of period t the bank chooses B_t and S_{It} :

$$\max_{\{S_{It}, B_t\}} \mathbb{E}_t \left[\Lambda_{t,t+1}^I N_{It+1} \right] \quad s.t. \quad (3.1), (3.10), (3.11)$$

with first-order conditions:

$$\mu_t^I + \lambda_t = (1 + \lambda_t) \mathbb{E}_t \left[\Lambda_{t,t+1}^I R_{It+1}^K \right] \quad (3.13)$$

$$\mu_t^I + \omega_t \lambda_t = (1 + \lambda_t) \mathbb{E}_t \left[\Lambda_{t,t+1}^I \right] R_t^B \quad (3.14)$$

Combining equations (3.12)–(3.4) we can derive the following two equations which

shed light on the model intuition

$$\begin{aligned}\mathbb{E}_{t-1} [(1 + \lambda_t) \Lambda_{t,t+1}^I (R_{It+1}^K - R_t^B)] &= \lambda_t (1 - \omega_t) \\ \mathbb{E}_{t-1} [(1 + \lambda_t) \Lambda_{t,t+1}^I (R_t^B - R_{It-1}^D)] &= \mathbb{E}_{t-1} [\lambda_t (\omega_t - \nu)]\end{aligned}$$

According to the first equation expected the gross return to capital, $\mathbb{E}_{t-1} [R_{It+1}^K]$, equals the cost of interbank borrowing, R_t^B , only if the incentive constraint does not bind or if there is no friction on the interbank market ($\omega_t = 1$). If, however, $\omega_t < 1$ and $\lambda_t > 0$, banks on the receiving side of the interbank market are funding constraint and cannot extend their lending activity even though that would be profit increasing. The second equation shows that for $\lambda > 0$ and $\omega_t > \nu$, i.e. a less frictional interbank than deposit market, a positive spread between marginal costs in the deposit and the interbank market emerges. If the deposit market is relatively more frictional than the interbank market ($\nu < \omega_t$), then it is easier for banks I to get funding from the interbank market relative to the deposit market. In order to get an additional unit of deposits, the bank needs to hold a higher amount of net worth in the future relative to a situation in which the bank wants to get an additional unit of interbank borrowing. As banks I demand relatively more interbank loans than deposits, the price for interbank loans, R_t^B , is larger than that for deposits, R_{It-1}^D .

3.5 Final Good Producer

Both final good producer and capital good producer exist independently on each island h . The perfectly competitive final good producer on island h combines labor and capital using a Cobb-Douglas production function to produce a homogeneous final output good:

$$Y_{ht} = A (K_{ht})^\alpha L_{ht}^{1-\alpha} \quad (3.15)$$

The factor input demand is determined by

$$w_{ht} = (1 - \alpha) \frac{Y_{ht}}{L_{ht}} \quad (3.16)$$

$$Z_{ht} = \alpha \frac{Y_{ht}}{K_{ht}}, \quad (3.17)$$

where Z_{ht} denotes the marginal return on capital and A_t is a productivity parameter. To obtain funds to invest into new capital and maintain the old capital stock the final good producer on island h issues equity at price Q_{ht} to the island's banks. With this loan the firm buys new and refurbished capital from a capital good producer. Due to perfect competition in the final good market the price for capital is also Q_{ht} .

3.6 Capital Good Producer

The capital good producer buys the old depreciated capital stock at the end of each period t at price Q_t and produces new capital using the final good as the only input. Old capital can be refurbished at unit costs but the production of new capital induces transformation costs $\mathcal{F}(I_{ht}/I_{ht-1})$. The new capital is then sold, still at period t , to the final good firm also at price Q_{ht} . Since the capital good producer is owned by the island's household future profits are discounted with the pricing kernel $\Lambda_{ht,t+s}$.

$$\max_{I_{ht}} \mathbb{E}_t \left[\sum_{s=0}^{+\infty} \Lambda_{ht,t+s} \left\{ Q_{ht+s} I_{ht+s} - \left[1 + \mathcal{F} \left(\frac{I_{ht+s}}{I_{ht+s-1}} \right) \right] I_{ht+s} \right\} \right]$$

The price of capital is hence determined by

$$Q_{ht} = 1 + \mathcal{F} \left(\frac{I_{ht}}{I_{ht-1}} \right) + \frac{I_{ht}}{I_{ht-1}} \mathcal{F}' \left(\frac{I_{ht}}{I_{ht-1}} \right) - \Lambda_{ht,t+1} \left(\frac{I_{ht+1}}{I_{ht}} \right)^2 \mathcal{F}' \left(\frac{I_{ht+1}}{I_{ht}} \right) \quad (3.18)$$

Following [Mendoza \(1991\)](#), we assume that $\mathcal{F}(I_{ht}/I_{ht-1}) = k/2 \cdot (I_{ht}/I_{ht-1} - 1)^2$.

3.7 Uncertainty

To implement uncertainty into our model we use a stochastic volatility framework. To this end we assume that the safe fraction of interbank lending, ω_t , follows an AR(1)–process:

$$\log \omega_t = (1 - \rho_\omega) \log \bar{\omega} + \rho_\omega \omega_{t-1} + \sigma_{\omega t-1} \varepsilon_t^\omega \quad (3.19)$$

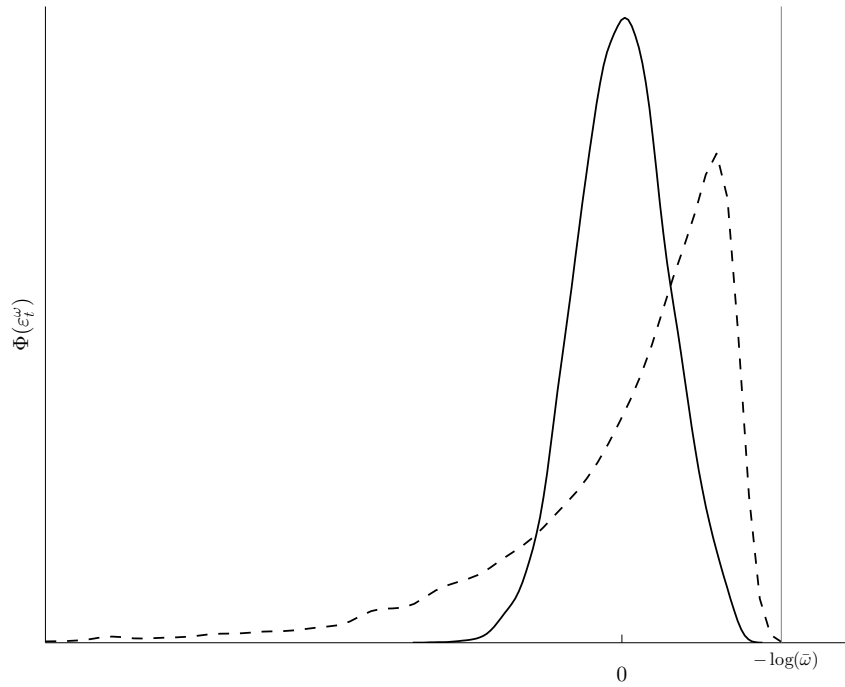
where $\bar{\omega}$ denotes the steady state degree of interbank friction at which the incentive constraint is satisfied with equality and $\varepsilon_t^\omega \sim \mathcal{N}^{trunc}(0, 1)$. Note that the fraction, ω_t , of non-divertable interbank lending, has to lie in the interval $[0, 1]$. This imposes a restriction on the distribution from which ε_t^ω is drawn: the largest effect of a shock to ε_t^ω on ω_t is on impact. Thus, it must hold: $\bar{\omega} \varepsilon_1^\omega \leq 1$, where $t = 1$ is the impact period. The largest possible value for ε_1^ω agents expect to be drawn is therefore $\varepsilon_1^\omega \leq -\log(\bar{\omega})$. The distribution has to be truncated at $-\log(\bar{\omega})$. The standard deviation, σ_t^ω , of the first moment shock is time-varying and follows an AR(1)–process as well:

$$\log \sigma_{\omega t} = (1 - \rho_{\sigma_\omega}) \log \bar{\sigma}_\omega + \rho_{\sigma_\omega} \sigma_{\omega t-1} + \eta_\sigma \varepsilon_t^{\sigma_\omega} \quad (3.20)$$

where $\bar{\sigma}_\omega$ denotes the steady state value of $\sigma_{\omega t}$ and $\varepsilon_t^{\sigma_\omega} \sim N(0, 1)$ and η_σ the dispersion of the uncertainty shocks $\varepsilon_t^{\sigma_\omega}$. We are interested in analyzing the ex-ante effect of an increase in interbank uncertainty. That is, we are not interested in the ex-post effects of drawing first-moment shocks from the broader distribution. Rather we want to consider the contemporaneous effects of learning that future shocks will be drawn from a broader distribution. A second order approximation would only allow us to elaborate on the joint effects of a second moment shock with its cor-

responding first moment shock (see [Fernández-Villaverde, Guerrón-Quintana, and Rubio-Ramírez, 2010](#)). In a second order approximation stochastic volatility, additionally, enters the approximated policy function through the constant.⁸ Thus, for uncertainty to have effects on the model dynamics, which are isolated from its corresponding first moment shock, we need to rely on a third order approximation (see [Fernández-Villaverde, Guerrón-Quintana, Rubio-Ramírez, and Uribe, 2011](#)). More technically, in a second order approximation to the policy function, $\varepsilon_t^{\sigma\omega}$ enters the function through cross-products only with its own first moment shock ε_t^ω (the coefficients of other terms including $\varepsilon_t^{\sigma\omega}$ are zero). In a third order approximation $\varepsilon_t^{\sigma\omega}$ enters the approximation also through cross-products with the state vector of our model. In that sense uncertainty is now able to interact with the state variables (on impact) without having to draw any first moment shocks. Figure 5 shows the effects of a second moment shock on the probability distribution of ε_t^ω .

Figure 4: Uncertainty Shock



Notes: For both truncated normal distributions the expected value is zero. The solid curve indicates the probability distribution over ε_t^ω before the uncertainty shock occurs. The dashed curve indicates the distribution over ε_t^ω after the shock to dispersion occurred. Both distributions are truncated at $-\log(\bar{\omega})$.

The uncertainty shock $\varepsilon_t^{\sigma\omega}$ is observed by both banks at the beginning of period t . Both banks thus know with certainty that next period's ε_{t+1}^ω will be drawn from a

⁸This is generally also true for the homoskedastic case discussed in [Schmitt-Grohé and Uribe \(2004\)](#).

broader distribution with the same expected value. This in turn leads to an increase in the dispersion of beliefs about the expected strength of the interbank market friction, however the beliefs remain homogeneous across islands.

An increase in uncertainty, in general, increases the probability of drawing more extreme (first-moment) shocks. Heightened uncertainty shifts probability mass from the mean to the tails of the distribution, while leaving the ex-ante expected value, $\bar{\omega}$ unaffected. Banks are owned by the risk-averse household and therefore dislike any covariance between expected marginal utility and expected interbank market friction (see Equation (??)). Hence, banks of type P require a higher risk premium on interbank lending, the more pronounced expected movements in ω_{t+1} are. Through the incentive constraint this corresponds to the requirement of a higher equity buffer to insure a given amount of interbank funding against defalcating. As bank on I cannot increase equity instantaneously the incentive constraint will tighten and banks on I become funding constraint. Thus, uncertainty shocks constraint interbank liquidity flows. Banks on island P will hence provide less interbank funding such that the incentive constraint is satisfied. Banks on I reduce their loan supply. Investment and production decrease, depressing the equity value of entrepreneurs. Since banks are the holder of this equity, they will suffer losses on their assets and thus, via the interbank market friction, will become even more liquidity constraint. Thus, increasing uncertainty triggers a vicious cycle of deteriorating banks' equity and decreasing liquidity supply. Therefore, similar to a financial accelerator, our model features an accelerator via banks' balance sheets.

3.8 Market Clearing

Markets clear on each island. The good market clearing condition requires

$$Y_{ht} = C_{ht} + \left[1 + \mathcal{F} \left(\frac{I_{ht}}{I_{ht-1}} \right) \right] I_{ht} \quad (3.21)$$

and the clearing of the retail loan market requires

$$S_{ht} = K_{ht+1} \quad (3.22)$$

Finally, the law of motion for the capital stock is given by

$$K_{ht+1} = I_{ht} + (1 - \delta)K_{ht} \quad (3.23)$$

The full model is described by equations (3.1)–(3.23).

4 Results

4.1 Calibration

The calibration of our model for the simulation exercise is summarized in Table 1. The calibration of most parameters is standard. We choose $\beta_P = .99$ which corresponds to an annual steady state deposit rate on island P of about 4 %. Households on island I are more impatient and require a higher steady state interest compensation of about 16.7 % which corresponds to $\beta_I = 0.96$. We choose χ_P and χ_I such that in steady state aggregate hours supplied are 0.33 on both islands. We follow [Gertler and Kiyotaki \(2011\)](#) and set the habit parameter $a = 0.5$ and $\varphi = 0.1$. The capital share in aggregate production $\alpha = 0.33$ on both islands. We follow [Schmitt-Grohe and Uribe \(2003\)](#) and set $k = 0.028$. The quarterly depreciation rate δ is set to 2.5 %.

Table 1: Parameter Calibration

β_P	0.99	household discount factor
β_I	0.96	
χ_P	7.88	
χ_I	6.18	weight on labor disutility
a	0.5	habit parameter
φ	0.1	inverse Frisch elasticity
k	0.028	capital adjustment cost parameter
α	0.33	capital share
δ	0.025	depreciation rate
ξ	0.4	start-up share for banker
ν	0.4	safe fraction of deposits
$\bar{\omega}$	0.6	s.s. safe fraction of interbank friction
Γ	0.22	s.s. deposit market friction
$\bar{\sigma}$	0.15	steady state dispersion of ε^ω
ρ_{σ_ω}	0.66	persistence of uncertainty shock

We assume that the start-up transfer to set up office each island's banker receives 40 % of last periods aggregate banks' net worth on each island. We set this parameter higher than in [Gertler and Kiyotaki \(2011\)](#) for two reasons: first, since each banker only accumulates net worth for one period instead of 40 as in Gertler and Kiyotaki, a low ξ would correspond to almost zero transfers. Second, and closely related, net worth is a crucial variable in our model since shocks, that hit the economy affect banks via their net worth. Since bankers live only for one period, a low very ξ would thus strongly limit the effects of these shocks as the intertemporal transmission of net worth effects would be strongly congested. We follow [Gertler and Kiyotaki \(2011\)](#) and set $\bar{\omega} > \nu$, i.e. we assume the interbank market to be less frictional

than the deposit market. We choose $\nu = 0.4$ and $\bar{\omega} = 0.6$ which corresponds to a total of 32.8 % of assets that can be diverted in steady state. As a comparison [Gertler and Kiyotaki \(2011\)](#) assume the total fraction of assets divertable to be 38.3 % (12.9 %) when interbank market is working frictionless (frictional). We set the reduced form deposit market friction Γ such that the steady state leverage is about 3. This guarantees that the steady state is strictly positive. For the uncertainty shock to the interbank market friction we assume that the steady state dispersion of ε^ω is 0.15. We, moreover, assume that the second moment shock to ω_t has a persistence of $\rho_{\sigma_\omega} = .66$. Therefore, after one year about 20 % of the initial increase in uncertainty persist.

4.2 Interbank market uncertainty shock

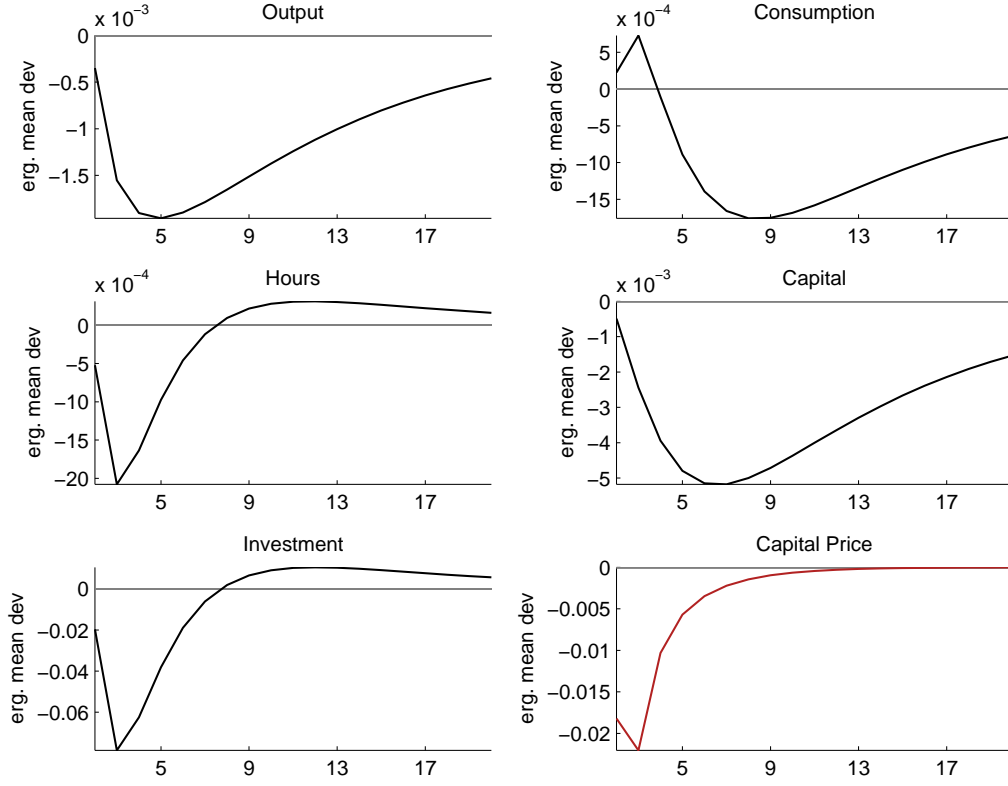
We now turn to the analysis of the effects of uncertainty shocks in the interbank market on the economy. As discussed in Section 3.7, we model uncertainty as an increase in the dispersion of beliefs about the fraction of interbank loans expected to be repaid, i.e. we model an uncertainty shock in the interbank market through an increase in $\varepsilon_t^{\sigma_\omega}$ (see Equation (3.20)). Simulating the model with Dynare (see [Adjemian, Bastani, Juillard, Karam, Maih, Mihoubi, Perendia, Pfeifer, Ratto, and Villemot, 2014](#)), we use a third order approximation of the policy function to be able to consider the effects of $\varepsilon_t^{\sigma_\omega}$ independently of the corresponding first moment shock ε_t^ω . Using a third order approximation often leads to explosive behavior of the generated time series. To overcome this problem we rely on the pruning procedure as suggested by [Kim, Kim, Schaumburg, and Sims \(2008\)](#) and generalized by [Andreasen, Fernández-Villaverde, and Rubio-Ramírez \(2014\)](#). We refer the reader to Appendix A for details on how the IRFs are computed.

Figures 5 and 6 show the endogenous model responses to an uncertainty shock. All responses are measured as percentage deviations from the ergodic mean. An increase in uncertainty reduces liquidity supplies through the interbank market as banks on type P islands become less sure about the size of the fraction of loans they can expect to be repaid from borrowing banks. In response to this reduction banks on the receiving side of the interbank market partially substitute into deposits, which drives up deposit rates. Since the deposit market is frictional as well and $\bar{\omega} > \nu$, a full substitution is not possible since each unit of deposit requires a higher insurance premium than interbank funding. This means that for an additional unit of deposit relative more net worth has to be pledged by the borrowing bank than for an additional unit of interbank loans. Consequently, banks of type I become funding constraint and have to cut down their loan supply which is mirrored in a decrease in investment and capital. The reduction in investment activities increases the expected return $\mathbb{E}_t[R_{t+1}^K]$ on investment projects and increases, therefore, the supply of firms' equity. However, demand for this equity is low as banks cannot get

the liquidity to purchase it. Therefore, asset prices drop. As banks hold equity in their balance sheets the reduction in equity prices hits banks on their asset side and lead to a deterioration of net worth. As a consequence banks of type I become more funding constraint and have to further cut down their lending activities. This is reflected by the increase in the shadow value of the incentive constraint. To ease the funding constraint banks of type I start to deleverage to improve their net worth position. This deleveraging cycle imposes real costs onto the economy as the capital stock remains depressed for an extended period of time.

Figure 5: Uncertainty shock in Interbank Market

(a) Reaction of real variables



(b) Reaction of financial variables

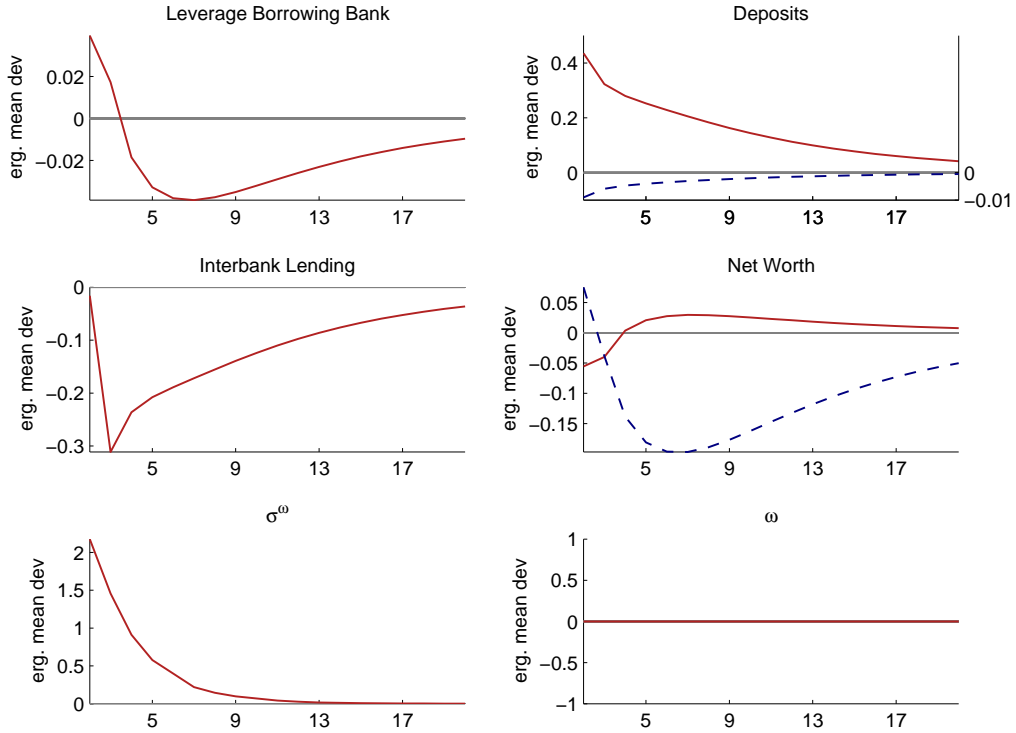
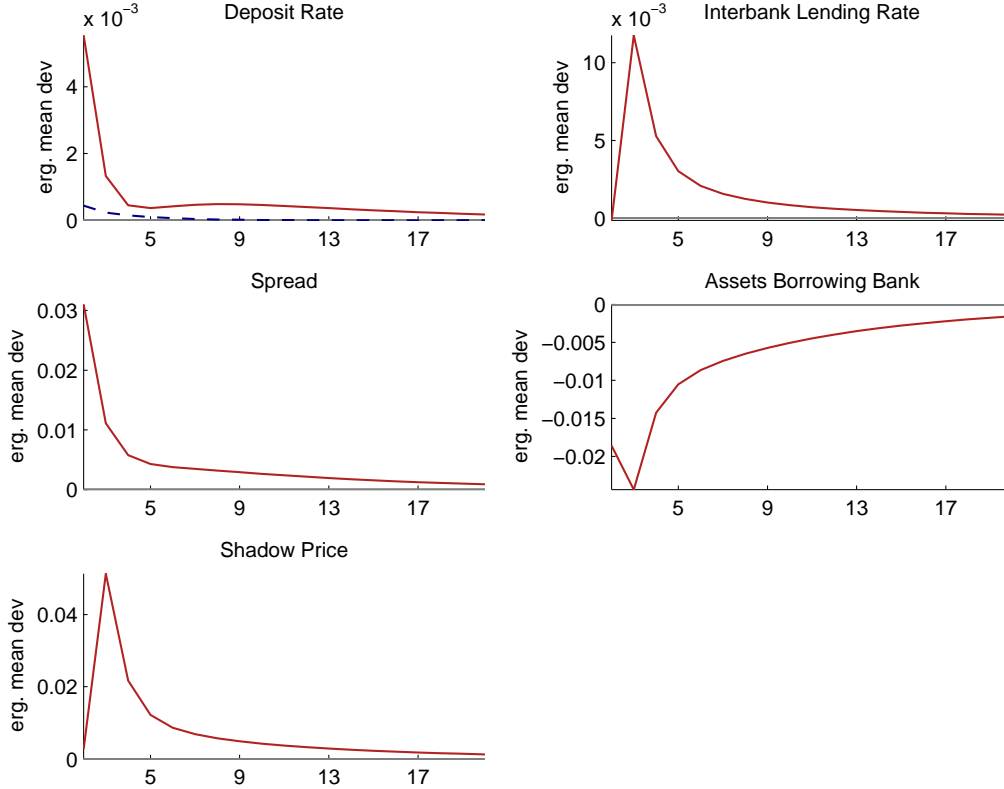


Figure 6: Uncertainty shock in Interbank Market (continued)



Notes: This simulation shows the effect of a exogenous shift in the probability distribution from which ε_t^ω will be drawn. Prior to the shock $\varepsilon_t^\omega \sim \mathcal{N}(0, 1)$ and after the shock $\varepsilon_t^\omega \sim \mathcal{N}(0, 4)$. All parameters are calibrated as shown in Table 1. The depicted variables are those from the impatient island. Impulse responses are calculated in percent deviations from the ergodic mean.

5 Conclusion

In this paper we introduce interbank market uncertainty into a DSGE setup to model the effects of a sudden increase in counterparty risk onto financial markets and the real economy. We build upon a standard RBC model with heterogeneous agents augmented by a market for financial intermediation with frictions. Banks finance loans with household deposits, interbank lending and equity. Following [Gertler and Kiyotaki \(2011\)](#) we introduce an agency problem into the interbank market to impose a liquidity constraint on financial intermediaries: we assume that banks can divert a fraction of their total assets. Thus, banks are only able to acquire funds from both the interbank and the deposit market if creditors anticipate that there is no incentive to divert the funding. As a novel feature of our model we introduce uncertainty in the interbank market. When banks give loans to one another they have a probability distribution over the fraction they expect to be repaid. We define interbank uncertainty as the dispersion of this probability distribution, which is

time-varying.

Interbank uncertainty introduces a new transmission channel through which financial frictions affect the economy. An increase in uncertainty raises doubts about the fraction of interbank loans to be repaid. This reduces interbank lending activities. Banks in need for interbank funding become liquidity constraint and must deleverage. Loan supply to the real economy, investment and production decrease, depressing the equity value of entrepreneurs. Since banks are the holder of this equity, they will suffer losses on their assets and thus, through the interbank market friction, will become even more liquidity constraint. Therefore, increasing uncertainty triggers a vicious cycle of deteriorating banks' equity, deleveraging and decreasing liquidity supply. Similar to a financial accelerator, our model features an accelerator through banks' balance sheets.

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Appendix

A Simulation of Impulse responses

To compute the impulse response functions to an uncertainty shock we follow [Fernández-Villaverde, Guerrón-Quintana, Rubio-Ramirez, and Uribe \(2011\)](#) and derive the IRFs as percentage deviations from the model's ergodic mean instead of the steady state. In a third order approximation, the expected value of the policy function depends on several constant terms: the steady-state value, a constant term derived from the second order approximation and the variance of the shocks derived from the third order approximation (in case of an asymmetric shock distribute). That is, changes in the volatility of shocks changes the ergodic mean relative to the steady state (see e.g. [Andreasen, 2012](#)). Therefore, evaluating the policy function in an environment without stochastic shocks does not correspond to the deterministic steady state as it is the case under a first order approximation. We therefore compute the IRFs from the ergodic mean.

We follow [Cesa-Bianchi and Fernandez-Corugedo \(2013\)](#) for constructing impulse responses. We use a two step procedure:

Step A In the first step we simulate the model's ergodic mean

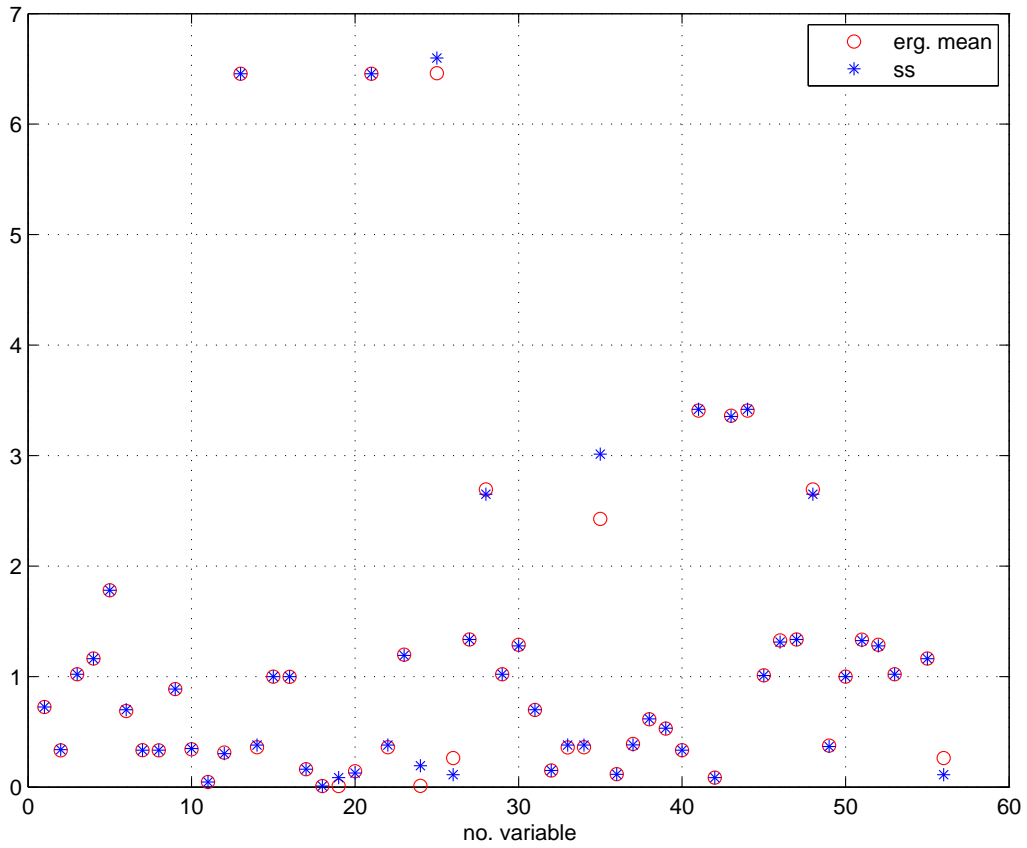
1. Draw a series of random shocks $\epsilon_t = (\epsilon_t^X, \epsilon_t^{\sigma_X})$, $X \in \{\omega, A\}$ (taking into account the respective standard deviation of the shock distribution) for $N = 25000$ periods.
2. Starting from the steady state, simulate the model using ϵ_t to the simulated time series get $Y_t \in \mathbb{R}^{n \times N}$ with n being the number of model variables.
3. Discard the first B burn-in periods of the simulated observations and calculate the ergodic mean of the model, first over all remaining $N - B$ period and second, over only $N - B - 500$ periods. If the maximum absolute change in the ergodic mean over the last 500 periods is smaller than 10^{-4} the ergodic mean, Y_0 , is found. Otherwise, we stack another 5000 shock periods below ϵ_t and repeat steps 2. and 3. until convergence.

Step B In the second step we calculate the impulse responses as deviations from Y_0 . For example, impulse responses in reaction to the uncertainty shock, $\epsilon_t^{\sigma_X}$, are calculated as:

1. Draw a series of random shocks $\epsilon_t^{\sigma_X}$ (taking into account the respective standard deviation of the shock distribution) for N periods ($N = 100$)

2. Starting from the ergodic mean, Y_0 , simulate the model using $\epsilon_t^{\sigma^X}$ and to get $Y_t^1 \in \mathbb{R}^{n \times N}$.
3. Add one standard deviation σ^X to $\epsilon_t^{\sigma^X}$ in period 1 only to get $\tilde{\epsilon}_t^{\sigma^X}$
4. Starting from the ergodic mean Y_0 , simulate the model using $\tilde{\epsilon}_t^{\sigma^X}$ and get Y_t^2
5. IRFs are calculated as $Y_t^2 - Y_t^1$
6. Repeat steps 1. to 5. 1000 times and calculate the average IRFs as percentage deviation from the ergodic mean.

Figure 7: Simulated Ergodic Mean versus Steady State



Notes: This simulation shows the effect of an exogenous shift in the probability distribution from which ε_t^ω will be drawn. Prior to the shock $\varepsilon_t^\omega \sim \mathcal{N}(0, 1)$ and after the shock $\varepsilon_t^\omega \sim \mathcal{N}(0, 4)$. All parameters are calibrated as shown in Table 1. The depicted variables are those from the impatient island. Impulse responses are calculated in percent deviations from the ergodic mean.