Italian Economic Journal
https://doi.org/10.1007/s40797-019-00104-0

RESEARCH PAPER

The Real Effects of Endogenous Defaults on the Interbank Market

Massimo Minesso Ferrari[1,2]

Received: 13 February 2019 / Accepted: 15 July 2019

Abstract
This paper explains the reaction of the interbank market to confidence shocks by means of a micro-founded general equilibrium model with heterogeneous banks. The contribution of the model is threefold: first, it micro-founds the decision problem of banks, by explicitly relating counterparty risk to the issuance of new credit on the interbank market and showing that this channel amplifies the effects of the shocks; second, the model analyses the effects of a pure confidence crisis (i.e. when banks assess that their counterparts on the interbank market are more likely to default despite the fundamentals remain sound) showing that its effects are long-lasting and severe (i.e. a 1% increase in risk generates a contracts GDP by 1.5 bp and investments by 50 bp); third, the model shows that conventional policies to offset a confidence crisis (i.e. monetary policy cannot restore trust on the interbank market and solve the liquidity crisis induced by a confidence shock induces).

Keywords Macrofinance · Contagion · DSGE · Interbank Market · Heterogeneous Agents · Monetary Policy

JEL Classification E44 · E32 · E52 · E58 · D85

The views expressed are those of the author and do not necessarily reflect those of the European Central Bank or its Executive Board.
I am grateful to Domenico Delli Gatti, Gianluca Femminis, Alessandro Flamini, Giovanni Lombardo, Maria Sole Pagliari, Justine Pedrono, Patrizio Tirelli and participants at seminars at the Catholic University of Milan and the Bicocca University of Milan.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s40797-019-00104-0) contains supplementary material, which is available to authorized users.

✉ Massimo Minesso Ferrari
massimo.ferrari1@ecb.europa.eu

1 European Central Bank, Frankfurt-am-Main, Germany

2 Catholic University of Milan, Milan, Italy

1 Introduction

After the default of Lehman Brothers, the US interbank market became illiquid, leading to a further tightening of the liquidity constraints faced by banks (already in distress).[1] Large stimulus by central banks had limited effects as banks started to change the composition of their balance sheets using excess resources to purchase risk-less assets, crippling the transmission of monetary policy (see Fig. 1). This led to a collapse in interbank and final credit, investment and aggregate demand (Brunnermeier 2009; Angelini et al. 2011).[2]

A central role was played by financial agents' expectations on the solvency of their counterparts with standard measures of risk, such as the VIX, spiking during the GFC, see De Socio (2013).

This paper analyzes the role of counterparty risk on the interbank market for the portfolio choices of banks and how it affects the real side of the economy. In particular, the analysis is based on a general equilibrium model where the decision problem of banks is micro-founded, in that it assumes that the issuance of interbank credit explicitly depends also on the interbank loan default probability. This feature represents a departure from previous general equilibrium models[3] as the default probability is not modeled as a completely exogenous process or as a choice variable for debtors, but, on the contrary, it depends upon the returns on retail activity (which have a stochastic component). That is to say, a bank defaults on interbank credits if these returns are sufficiently low (i.e. end-of-period assets, net of deposits, are less than outstanding interbank liabilities) and the bank's net worth is not high enough to compensate the assets-liabilities gap. Lending banks endogenize that probability, which depends—among other factors—also on the amount of interbank credit issued by adjusting the volume of funds invested on the interbank market to achieve the desired exposure to counterparty risk.[4] To the best of my knowledge this is the first paper to fully endogenize defaults on the interbank market. This setting is particularly interesting as it allows to quantify the effects of interbank default risk on business cycle fluctuations. It can also be used to study pure "confidence" crises (i.e. when banks *perceive* interbank credit as riskier, despite steady fundamentals) whose effects are found to be sizable and long lasting. This paper also helps explain, in a full micro-founded general equilibrium framework, the behavior of banks during the Global Financial Crisis (GFC), when the lack of trust among financial agents led to the collapse of the interbank market. With this aim, credit institutions are assumed to be heterogeneous along two dimensions: first, banks in each period may be borrowers or lenders on the interbank market; second, returns on retail loans have a stochastic component that is bank-specific; which determines a threshold for returns below which a bank borrowing on the interbank market defaults on interbank credit. Such threshold, however, depends also on bank's net worth because the higher the net worth, the more a bank can absorb losses without defaulting.

[1] See Albertazzi et al. (2009), Gorton (2009) and Affinito and Piazza (2018).

[2] See also Delli Gatti (2012) , Guillen (2011), Allen et al. (2009).

[3] See Dib (2010), Hilberg and Hollmayr (2011), Carrera and Vega (2012), Takamura (2013).

[4] In a nutshell, lending banks stop issuing credit on the interbank market when risk-weighted returns on interbank loans become lower than the opportunity cost of capital.

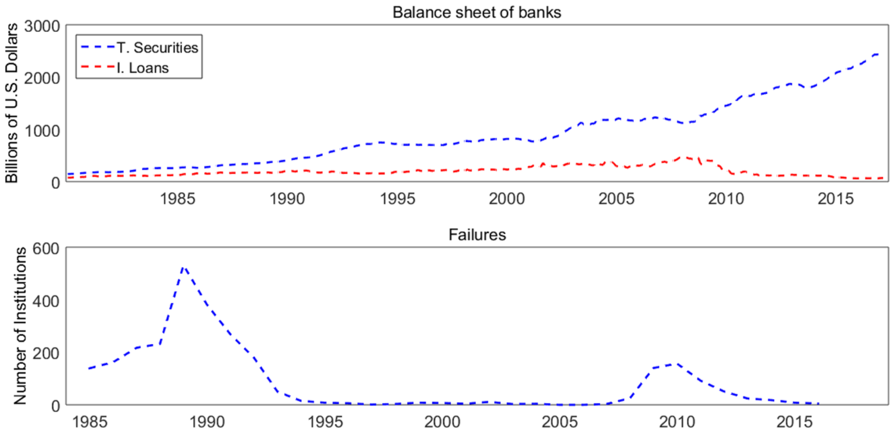

Fig. 1 The banking system in the US. Notes: Interbank loans and treasury securities held by the top 100 U.S. financial institutions and delinquency rates on commercial and industrial loans. Sources: Federal Deposit Insurance Corporation, Board of Governors of the Federal Reserve System. Notice how the two series have a positive correlation before the Global Financial Crisis and then start to diverge

Therefore, this paper gives three main contributions to the literature: first it presents a general equilibrium model in which the default probability is fully endogenous (i.e. it is the complex convolution of bankers choices, firms decisions and the state of the economy); second, it shows that confidence shocks (i.e. an increase in the perceived risk of interbank lending) across banks can precipitate real recessions, in spite of starting strong fundamentals; third it explains how the interbank market might "freeze" (i.e. experience a sharp reduction of credit across financial institutions), the channels through which this propagates to the real economy and the reasons why conventional policies are ineffective in countering these shocks. Notably, as the probability of default increases interbank credit becomes riskier and *effective expected returns* on interbank loans decrease. Bankers, therefore, find it optimal to disinvest from the interbank market and, then, purchase risk-free assets as risk-weighted returns on interbank credit fall below the risk-free rate. This mechanism eventually leads to the collapse of final credit.[5] Finally, since credit risk is the main driver of the banks choices, standard monetary policy may not be adequate to counteract the crisis.

The key part of the model is the banking sector. Banks can allocate funds between: (i) final loans to firms, (ii) interbank loans to other financial institutions, (iii) risk-free assets. The stylized balance sheet of banks presents the fundamental choice problem for bankers: interbank lending has higher returns than risk-free assets, but is subject to counterparty risk. All these aspects are taken into account when bankers choose how to allocate excess resources (i.e. funds not used to grant loans to firms).

Ceteris paribus, bankers know that each additional unit of credit makes debtors more leveraged thus increasing the default probability. When *expected returns* (defined as the gross rate weighted for the default probability) on interbank lending equal the riskless rate, bankers find optimal not to issue additional credit to other banks. This implies

[5] Iyer et al. (2014), Cignano et al. (2016) and Barone et al. (2016) provide empirical evidence of this phenomenon after the GFC.

that a sufficiently large increase in the default probability can cripple the functioning of the interbank market.

As a corollary, when leverage increases, ceteris paribus, interbank credit decreases (as banks become more fragile) and fewer loans are granted to firms which, in turn, contracts output. Therefore, this model is also suitable to investigate the relation between real and financial shocks, as well as the nexus between default probability on the interbank market and credit. In this regard, the key difference from previous contributions is that the default probability is the outcome of non-cooperative choices of different agents in the economy and aggregate shocks.

The rest of the model builds on Gertler and Kiyotaki (2010) and Gertler and Kiyotaki (2015) and is estimated with Bayesian methods.[6]

1.1 Literature Review

There is a vast literature analyzing the role of interbank market risk (during and after the GFC) and its connection with monetary policy both empirically and by means of theoretical models.

Among the vast empirical literature on the topic, Diebold (2009) uses vector autoregressions to measure spillovers of tighter financial conditions. Jimènez et al. (2014), Iyer et al. (2014), Becker and Ivashina (2014) use loan and firm level data to document how less interbank credit translates in fewer final loans to firms; similarly Cignano et al. (2016) and Barone et al. (2016) document the effects on real activity of credit crunches in Italy. Iyer and Peydrò (2011) addresses a similar question with a natural experiment and focusing on macro-variables while Jimènez et al. (2014) and Vasso et al. (2015) explore the relationship between risk-taking and monetary policy. Finally Hong et al. (2009) and Jorion and Zhang (2009) focus on the role of risk in credit markets. Despite the different data sources and empirical strategies used the general finding is that spillover from interbank credit to real activity are large and that credit strongly responds to risk shocks.

Since the seminal works by Allen and Gale (2000) and Diamond and Rajan (2001), there is also a vast literature on counterparty and default risk, mostly from the microeconomics of banking. More recent contributions focus specifically on the interbank market, for example: Heider et al. (2015), Archarya et al. (2011), Archarya and Skeie (2011), Bias et al. (2016) and Xuewen (2016). Differently from that strand of literature, this paper develops a full general equilibrium model with a complex financial sector. To assess the role of interbank risk on the real economy, on one hand, the financial sector block needs to be rich enough to allow for endogenous defaults and risk propagation. On the other hand, the model needs to be solved in general equilibrium to assess spillovers from the interbank market to the real economy and vice versa.

Credit risk, defaults and financial contagion have been also studied in the context of the network literature, leading to theoretical models and empirical analysis of financial networks. Between others, Eisenberg and Noe (2001), Branch and Evans (2005), Delli Gatti and Longaretti (2006), Hommes (2006), de Grave et al. (2010), Gai and Kapadia (2010), Motta and Tirelli (2015), Haldane and May (2011), Bargigli et al.

[6] See Gertler and Kiyotaki (2010), Phelan and Townsend (1991) and Meeks et al. (2017).

(2015) and Affinito and Pozzolo (2017). Differently from that literature, however, this paper does not exploits the property of random graphs to study contagion. In this model credit relations are essentially bilateral between a lending bank and a borrowing bank on the interbank market. Risk arises from the possibility that a borrowing bank is not able to refund interbank loans at the end of the period. A single default does not generate aggregate consequences from direct contagion between banks (as in the network literature) but rather from the fall in output and capital returns in the following periods, as less credit is issued by the banking sector and the economy contracts. In this stance, the paper is closer to the "asset communality" explanation for financial contagion.

This paper also crucially builds on the macro-finance general equilibrium literature. In that literature, researchers have tried to relax the perfect competition assumption for financial and credit markets, finding that results are qualitatively and quantitatively different when financial frictions are taken into account. Gerali et al. (2010), Gertler and Karadi (2011), Dib (2010), Brunnermeier and Sunnikov (2014) and Gertler and Kiyotaki (2015) (later extended by Gertler et al. (2016) where banks are split in two categories: wholesale and retail) find that financial frictions have large amplification effects which may be non-linear. The way in which financial frictions are accounted for differs across authors but, broadly speaking, they can be divided into two categories: (i) market imperfections which lead to market power by some agents (generally financial intermediaries) or intermediation costs; (ii) moral hazard between borrowers and lenders, such as Boissay et al. (2016). The first attempt to incorporate moral hazard as a credit friction has been Bernanke et al. (1999), which defined the so-called financial multiplier. A drawback of many macro-finance models is the use of the representative agent approach to model banks; in that setting defaults are, by construction, impossible. As argued by Goodhart and Tsomocos (2009), however, default risk is a key component of banking crises and including defaults in DSGE models is a critical step to use them to explain such events. In this paper banks decisions are fully micro-founded and defaults are endogenous in a proper sense. Differently from contributions like Dib (2010) and Giri (2018) the default probability is not a choice variable for borrowing banks, which "optimally" choose a default probability on their liabilities, but rather arises from the complex convolution of bankers choices, the state of the economy and aggregate shocks. In this model, banks can default on interbank credit if end-of-periods assets, net of deposit, do not cover all interbank debts. End-of-period assets are a function of effective returns on loans, banks net worth, real variables and interest rates. Moreover, as banks choose the amount of interbank credit *at the beginning of the period*, expectations play an important role and lending banks optimize the amount of interbank credit granted to achieve the desired level of exposure to risk on the interbank market. These two channels are an innovative contribution to the DSGE literature and allow to (i) define the default probability as a proper endogenous variable, (ii) study the role of pure risk shocks, (iii) explain why banks rationally contract the supply of credit to the interbank market and quantify the real effects of that. In this sense, the model finds a "financial accelerator" role for interbank credit, similar to the role of credit to firms in Bernanke et al. (1999).

The paper proceeds as follows: Sect. 2 presents the model, Sect. 3 the data, Sect. 4 the Bayesian estimation (with robustness checks), Sect. 5 studies impulse response functions and Sect. 6 presents conclusions.[7]

2 The Model

The economy is populated by households, firms, banks, a government and a central bank.

Households own firms, consume differentiated goods, save trough deposits and pay taxes. A fraction (f) of an household's members are workers and another $(1-f)$ bankers. Workers supply labor to firms and earn wages; bankers run banks and return their profits[8] to households as dividends when the bank closes, which can occur in each period with probability σ. In that case, the banker becomes a worker while a worker takes her place as banker; initial capital is provided to new bankers by households. Within each household there is perfect consumption insurance meaning that returns from banking activity and wages are pulled together to finance households' expenses.

The real sector of the economy is composed by wholesale good producers, retailers and capital producers.

Wholesale good producers combine capital and labor to produce, in perfect competition, undifferentiated goods that are sold to retailers. They do not accumulate capital so, in each period, undepreciated capital and new investments are financed by bank loans. As in Gertler and Kiyotaki (2010) and Gertler and Kiyotaki (2015) firms are located on different areas and can borrow funds only from banks located on the same area. In each period there is an exogenous probability π^i that new investment opportunities arise in an area; in that case firms can install new capital. This formalism introduces, in a tractable way, a bank-specific shock to the retail loan demand. On the contrary, in a fraction $\pi^n = 1 - \pi^i$ of areas only undepreciated capital needs to be financed. To ensure perfect competition, at the end of each period there is free mobility of banks between areas.

Retailers acquire the output of wholesale good producers, differentiate it with negligible costs and sell it on a national market with some degree of market power. Following the Calvo formalism,[9] they are not able to update prices in every period.

Finally, there are capital producers that provide new capital goods combining undepreciated capital and a fraction of final goods.

The financial sector is composed by banks that are finitely lived and raise liquidity through deposits on a national interbank market. Each bank can invest in interbank loans, loans to firms (retail loans) or riskless assets. Allowing banks to invest in riskless assets generates a trade-off between risky loans and safe securities. In periods of high risk, banks may find optimal to hold more riskless assets, reducing the supply of loans to firms and, therefore, constraining production. This is the key channel through

[7] Further proofs and derivations are reported in the Online Appendix.

[8] As there is perfect competition, profits are defined as returns on the invested capital, there are no "extra profits".

[9] See Calvo (1983).

which risk on financial markets is transmitted to the real economy. As in Stiglitz and Greenwald (2003) only banks in areas without new investment opportunities acquire riskless assets; it will be proved later that this assumption holds endogenously in the model.

Each bank is run by a banker, who optimizes the capital structure to maximize the value of bank's capital at the end of the period.[10] As in Gertler and Karadi (2011), bankers can divert a fraction of the total volume of funds intermediated to households. In that case, the bank defaults and creditors get the remaining bank's assets; this generates moral hazard between bankers and depositors leading to the rise of an incentive compatibility constraint (ICC) for banking activity.[11] Each bank, at last, is located on a specific area and can change area only at the end of the period. While borrowing on a national market, bankers can lend only to firms located on their same area. Banks learn if in their area there are new investment possibilities only after that the period has already started. However, following Gertler and Kiyotaki (2015), they set the level of deposits at the beginning of each period; as a consequence some banks (those on n-areas) have excessive funds, while others (those on i-areas) have a deficit of liquidity. Finally, similar to Angeloni and Faia (2009), it is assumed that returns on investment projects are affected by a stochastic component with zero expected value.

The central bank sets the riskless rate and the government chooses the level of its consumption of final goods.

2.1 Households

The objective function of the representative household is:

$$E_t \sum_{t=0}^{\infty} \beta^t e_t \left[\ln\left(C - \varphi C_{t-1}\right)_t - \nu \frac{L_t^{1+\varepsilon}}{1+\varepsilon} \right] \tag{1}$$

with C consumption and L the fraction of time devoted to work. υ is the weight of labor disutility that is equal to the elasticity of leisure, ε is the inverse of Frish elasticity to labor supply, φ is the habit parameter and β the discount factor. Finally, e is a preference shock, that follows an AR(1) process.

D_h are deposits in one type of bank ($h = i, n$ depending on the area) with returns R_t^D,[12] T are lump-sum taxes, W the nominal wage, Π profits of firms and banks transferred to households[13] and P the price level. Households optimize Eq. (1) under the budget constraint.[14] FOCs are:

[10] It is assumed that bankers act in the interest of households: maximizing end of period net worth they maximize the funds that can be transferred to households in case the bank closes.

[11] This is a common way to model agency problems between lenders and borrowers, see Kiyotaki and Moore (1997), Krishnamurthy (2003) and Fostel and Geanakoplos (2009).

[12] It will be shown later that the interest rate on deposits is equal to the riskless rate.

[13] $\Pi_t = \Pi_t^B + \Pi_t^F$, with Π^B the dividends of banks and Π^F the profits of firms.

[14] Which is $C_t + D_{h,t+1} + \frac{T_t}{P_t} \leq \frac{W_t}{P_t} L_t + \frac{\Pi_t}{P_t} + \frac{R_t^D D_{h,t}}{P_t}$.

$$\frac{e_t}{C_t - \varphi C_{t-1}} - \varphi\beta \frac{e_{t+1}}{C_{t+1} - \varphi C_t} = \lambda_t^C \tag{2}$$

$$\upsilon L_t^{\epsilon} = \frac{W_t}{P_t}\lambda_t^C \tag{3}$$

$$E_t \beta^t \frac{\lambda_{t+1}^C}{\lambda_t^C} \frac{R_t^D}{P_t} = 1 \tag{4}$$

$$C_t + D_{h,t+1} + \frac{T_t}{P_t} = \frac{W_t}{P_t} L_t + \frac{\Pi_t}{P_t} + \frac{R_t^D D_{h,t}}{P_t} \tag{5}$$

with $\left\{\lambda_t^C\right\}_{t=0}^{\infty}$ the sequence of Lagrangian multipliers associated to the optimization problem and $\Lambda_t^C = \beta^t E_t\left(\frac{\lambda_{t+1}^C}{\lambda_t^C}\right)$ a stochastic discount factor.

Equations (2) and (3) describe the optimal choice of consumption and leisure, relating consumption choices and labor supply. Equation (4) describes the Euler condition on deposits requiring that the riskless rate is such that the present discounted marginal utility of future consumption equals the marginal utility of present consumption.

2.2 Firms

There are three types of firms: wholesale good producers, retailers and capital producers. Following the Calvo formalism, only a fraction $(1 - \theta_R)$ of retailers is able to reset prices at each time t; the remaining fraction (θ_R) keeps the price of the previous period.

2.2.1 Wholesale producers

Wholesale producers operate in perfect competition and produce homogeneous goods that are sold at a price P^W to retailers. The production function is:

$$Y_t = A_t K_t^{\alpha} L_t^{(1-\alpha)} \quad 0 < \alpha < 1 \tag{6}$$

with A total factor productivity, that follows an AR(1) process, and α the capital share. The optimal demand for capital and labor are:

$$\frac{1}{X_t}(1-\alpha)\frac{Y_t}{L_t} = \frac{W_t}{P_t} \tag{7}$$

$$\frac{1}{X_t}\alpha\frac{Y_t}{K_t} = Z_t \tag{8}$$

with Z gross profits per unit of capital.

$X_t = \frac{P_t}{\lambda_t^f}$ is the average mark-up of retail price over wholesale price ($P_t^W = \lambda_t^f$) and $\left\{\lambda_t^f\right\}_{t=0}^{\infty}$ the sequence of Lagrangian multipliers associated to the optimization problem.[15] Firms do not accumulate capital, therefore in each period they finance capital through bank loans. As long as they obtain credit from banks firms do not face any other friction and commit to pay back to creditors the gross profits per unit of capital. Credit is, therefore, equivalent to a claim on future returns on one unit of investments[16]:

$$Z_{t+1}, (1-\delta_K)\, Z_{t+2}, (1-\delta_K)^2\, Z_{t+3} \cdots$$

with δ_K the depreciation rate of capital. As wholesale producers operate in perfect competition returns on each unit of financed capital are:

$$R_t^{h,K} = \frac{\left[Z_t + (1-\delta_K)\, Q_t^h\right]}{Q_{t-1}^h} \tag{9}$$

with $h = i$ if the firm is operating on an area with new investment opportunities and $h = n$ if not. Define x as a stochastic shock on returns which is normally distributed with zero mean and variance h being i.i.d. across firms and areas. This is similar to the assumption used in Bernanke et al. (1999) to introduce volatility in returns on investments; similar to Bernanke et al. (1999) this component can be rationalized as sun spot shocks that hit firms at random. Ex-post returns on capital are:

$$R_t^{h,K} + x_t$$

Notice that expected returns on capital are $E(R_t^{h,K} + x_t) = R_t^{h,K}$. As entrepreneurs are penniless, this shock affects the payment that banks receive for capital services. The aggregate law of motion of capital is:

$$K_{t+1} = \{[I_t + \pi^i(1-\delta_K)K_t] + \pi^n(1-\delta_K)K_t\} = \{I_t + (1-\delta_K)K_t\} \tag{10}$$

with I new investments. Demand for loans on each type of area is:

$$S_t^h = \begin{cases} \pi^n\,(1-\delta_K)\,K_t & for\ h = n \\ \pi^i\,(1-\delta_K)\,K_t + I_t & for\ h = i \end{cases} \tag{11}$$

firms on i-areas need funds to refinance undepreciated capital and new investment projects. On the contrary, firms on n-areas cannot start new investment projects and need liquidity only to refinance undepreciated capital.

2.2.2 Retailers

Retailers acquire undifferentiated wholesale goods and transform them into differentiated final goods sold at the price P. They face a standard Dixit–Stiglitz demand

[15] Notice that $\frac{1}{X_t}$ is the real price of wholesale goods.

[16] Notice that this setting prevents the insurgence of a agency problem between bankers and entrepreneurs la Bernanke et al. (1999).

function[17] with ϵ the elasticity of substitution between different varieties of final goods. In each period retailers can reset prices with probability $1-\theta_R$. In that case the new price $P_{j,t} = P^*_{j,t}$ is set to maximize future expected profits:

$$\sum_{i=0}^{\infty} E_{t-1}\left[\theta_R \Lambda_t^C \left(\frac{P^*_{j,t} - P^W_{t+i}}{P_{t+i}}\right) Y_{j,t+i}\right]$$

FOCs lead to the definition of the optimal price equation:[18]

$$\sum_{i=0}^{\infty} E_{t-1}\left\{\theta_R \Lambda_t^C \left(\frac{P^*_{j,t}}{P_{t+i}}\right)^{-\epsilon} Y_{j,t+i}\left[\frac{P^*_{j,t}}{P_{t+i}} - \frac{\epsilon}{\epsilon-1}\frac{P^W_{t+i}}{P_{t+i}}\right]\right\} = 0 \tag{12}$$

with the aggregate price level being $P_t = [\theta_R P_{t-1}^{1-\epsilon} + (1-\theta_R) P^{*1-\epsilon}_{j,t}]^{\frac{1}{1-\epsilon}}$.

2.2.3 Capital Good Producers

Capital goods are produced combining old (undepreciated) capital and a fraction of final output with the technology: $f\left(\frac{I_t}{K_t}\right)K_t$.[19] Capital producers sell new capital at the price Q^i and maximize profits subject to the production function just presented. Optimality conditions define the Tobin's Q equation for the economy[20]:

$$Q^i_t = \left[f'\left(\frac{I_t}{K_t}\right)\right]^{-1} \tag{13}$$

2.3 Financial System

The financial system is populated by finitely lived banks which are run by bankers. Banks receive initial capital from households and raise deposits on a national market. If needed, banks can also access a national interbank market where they exchange funds one another.

With the funds raised financial institutions can provide (retail) loans to firms, acquire riskless assets or supply credit to other banks on the interbank market.

Following Gertler and Kiyotaki (2010), banks are constrained in their supply of retail loans, i.e. they can lend to only to firms located in their same area, while they borrow on a national level. At the end of each period, however, they can relocate to a different region; this assumption is needed to maintain perfect competition in the loan supply.

17 Dixit and Stiglitz (1977).

18 See Online Appendix B.1 for a complete derivation.

19 With $f'(\bullet) > 0$, $f''(\bullet) < 0$ and $f(0) = 0$. This production function allows for physical adjustment costs in the production of new capital following Kiyotaki and Moore (1997).

20 Notice that new capital is sold only on areas with new investment opportunities, therefore the superscript i. See Gertler and Kiyotaki (2010) for a detailed discussion.

Table 1 Stylized bank's balance sheet

Assets	Liabilities
Loans to firms	Capital
Interbank loans	Deposits
Riskless assets	Interbank debts

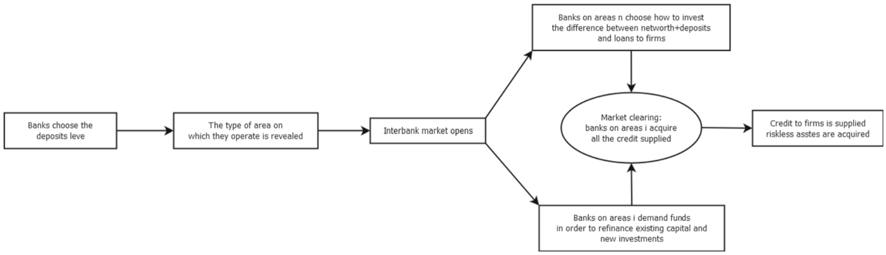

Fig. 2 Sequence of intra-period events for banks

Total assets is the sum of retail loans, riskless assets and interbank loans (if the bank *supplies* credit on the interbank market); on the liability side there are capital, deposits and interbank loans (if the bank *acquires* credit on the interbank market) (Table 1).

Banks in each period optimally choose the *net demand* of interbank loans and deposits, the amount of safe assets to acquire and the volume of retail loans to finance. As banks do not move between areas *within each period*, the demand for final loans depends on the realization of the area-specific investment shock. However, as bankers acquire deposits before that the investment shock is reveled, banks in n-areas hold more liquidity than retail loans demanded.[21]

With a frictionless interbank market, banks operating on n-areas would transfer to banks on i-areas the full amount of their surplus of funds and the total final credit supplied by the banking system would be equal to the sum of (aggregate) bank net worth and deposits. With frictions, however, banks do not invest the entire amount of excess resources in the interbank market. Frictions become more binding during recession, leading to a stronger contraction of credit in downturns and a worsening of the crisis.

The sequence of intra period events for banks is the following: first, banks choose on which area to operate; second, bankers set the demand for deposits; then the investment shock is realized; bankers enter the interbank market and the bond market; retail loans are financed; retail and interbank credit is refund; the period ends. This sequence of intra-period events follows closely Gertler and Kiyotaki (2010) (Fig. 2).

The moodel here departs from Gertler and Kiyotaki (2010) assuming that returns on final loans are affected by a the stochastic variable $x_{i,t}$, with $E\left(x_{i,t}\right) = 0$, $Var\left(x_{i,t}\right) = \sigma_x > 0$ and spanning on an interval $[-h; h]$ with a uniform distribution and probability

[21] Banks choose ex ante the level of deposits; therefore it is rational to choose a weighted average between the optimal value in the i and n state of the world.

$\frac{1}{2h}$.[22] This shock hits returns at random with sun spot costs or gains; investment projects, therefore, have some degree of uncertainty. Differently from Bernanke et al. (1999), where entrepreneurs own capital, in this model entrepreneurs are penniless. Therefore there are no agency problems between banks and entrepreneurs and, on average, banks obtain $R^{h,K}$ from their retail loan portfolio. Uncertainty, however, has an impact on the interbank market. Depending on the realization of x a bank may or may not obtain sufficient funds to pay back interbank credit.

Finally, as banks are fully own by households it is optimal for bankers to pay dividends only upon exit,[23] which can occur in each period with probability σ. Bankers optimize the capital structure to maximize the transfer upon exit. They can also divert a fraction ($A_t^{h,B}$) of total assets managed -excluded interbank credit-[24] to households, in that case the bank defaults. Bankers decide to divert assets if the value of the transfer is larger than the value of the bank, given by the expected value of net worth at the end of the period $\left(n_{t+1}^h\right)$; the banker's objective function is:

$$V_t^h = \max\left\{E_t\left(n_{t+1}^h\right); \theta\left(A_t^{h,B}\right)\right\} \tag{14}$$

with

$$A_t^{h,B} = \begin{cases} Q_t^i s_t^i - b_t^i & for\ h = i \\ Q_t^n s_t^n + b_t^n + f_t^n & for\ h = n \end{cases}$$

s^h is the volume of retail loans issued by each bank at the price Q^h, b the value of interbank loans,[25] f are riskless assets and θ the fraction of assets that bankers can divert. The superscript $h = i, n$ is needed as variables differ depending on the type of area where a bank operates. $A_t^{i,B}$ is the amount divertible funds for banks on i-areas, that is equal to the value of funds they intermediate minus interbank loans. As will be shown later on, those banks do not invest on riskless assets. On n-areas bankers can divert $A_t^{n,B}$ which equals the sum of final loans, interbank credit (which is an asset for these banks) and risk-free assets (f), i.e. the total amount of funds intermediated.

From Eq. (14) it is straightforward to see how an agency problem arises. Banks creditors do not lend to the bankers an amount of funds high enough to make $E_t\left(n_{t+1}^h\right) < \theta\left(A_t^{h,B}\right)$. In that case the bankers would divert θ of assets to households triggering a defaults. An (area-specific) ICC for bankers needs to be fulfilled for the credit system to function:

22 The shock is modeled following Bernanke et al. (1999), Angeloni and Faia (2009) and Diamond and Rajan (2001).

23 This is a common assumption in macro-finance models, as banks are financially constrained retaining earnings makes them less constrained and boosts profits. See Gertler and Karadi (2011) or Gertler and Kiyotaki (2010).

24 This is the simplest configuration of Gertler and Kiyotaki (2010) which is preferable in this setting to maintain tractability and focus on interbank risk.

25 Notice that interbank loans are an asset for lending banks and a liability for borrowing banks.

$$E_t(n^i_{t+1}) \geq \theta(Q^i_t s^i_t - b^i_t) \tag{15}$$
$$E_t(n^n_{t+1}) \geq \theta(Q^n_t s^n_t + b^n_t + f^n_t) \tag{16}$$

The bank's budget constraint, finally, is:

$$Q^i_t s^i_t = n^i_t + d_t + b^i_t \tag{17}$$
$$Q^n_t s^n_t + b^n_t + f^n_t = n^n_t + d_t \tag{18}$$

notice that interbank loans are a liability for banks on i-areas and an asset for those on n-areas which are also those acquiring riskless assets, see proposition (3).

2.3.1 Banks on Areas with New Investment Possibilities (*i*-Banks)

Banks on these areas face higher-than-expected demand for loans and, therefore, enter the interbank market demanding credit. As long as Eq. (15) holds, i-banks maximize expected end-of-period net worth:

$$E_t(n^i_{t+1}) = E_t[(R^{i,K}_t + x_{i,t})Q^i_t s^i_t - R^B_t b_t - R^D_t d_t + n^i_t] \tag{19}$$

with $R^{i,K}$ expected returns on loans to firms between t and t+1 (equal to $\frac{[Z_t+(1-\delta_K)Q^i_t]}{Q^i_t}$), d deposits and R^B the interbank interest rate between t and t+1. Notice that we can drop the index on interbank loans as they are a liability for this type of banks. The objective function of a representative i-bank is:

$$\begin{aligned}
&E_t \sum_{t=0}^{\infty} \Lambda^B_t n^i_{t+1} \\
&\Lambda^B_t \equiv (1-\sigma)\,\sigma^t\,\Lambda^C_t \\
&E_t(n^i_{t+1}) = R^{i,K}_t Q^i_t s^i_t - R^B_t b_t - R^D_t d_t + n^i_t
\end{aligned} \tag{20}$$

subject to the constraints of Eqs. (15) and (17). Equilibrium conditions are:

$$R^{i,K}_t - R^B_t = 0 \tag{21}$$
$$R^B_t - R^D_t = \frac{\lambda^i_t \theta}{\Lambda^B_t\left(1+\lambda^i_t\right)} \tag{22}$$
$$R^{i,K}_t Q^i_t s^i_t - R^B_t b_t - R^D_t d_t + n^i_t \geq \theta\left(Q^i_t s^i_t - b_t\right) \tag{23}$$

Notice that taking expectations: $E_t(R^{i,K}_t + x_{i,t}) = R^{i,K}_t$. $\{\lambda^i_t\}^{\infty}_{t=0}$ is the sequence of Lagrangian multipliers associated to the problem. Equation (21) defines the Euler condition for i-banks and the interest rate on the interbank market. As long as it holds, banks acquire all interbank credit supplied. Equation (22) defines the riskless rate as a mark-down on the interbank market rate. Combining Eqs. (21) and (22) one can show that the risk-free rate is also a mark-down on the returns on investments. The ICC holds with equality if $\lambda_t^i > 0$; that condition needs to be fulfilled to maximize profits, see Proposition (1) in the Online Appendix.

i-banks do not invest in risk-free assets, as returns on risk-free assets are always lower than the retail loan rate. This follows from Equs. (21)–(23); it can also be shown more formally, see Proposition (3) in the Online Appendix. A similar result is derived, under slightly different assumptions, by Stiglitz and Greenwald (2003). Substituting Eq. (23) into the budget constraint:

$$\tau_t^i n_t^i + \varpi_t^i b_t = \phi_t^i Q_t^i s_t^i \tag{24}$$

with $\tau \equiv (R_t^D + 1)$, $\varpi \equiv (R_t^D + \theta - R_t^B)$, $\phi \equiv (R_t^D + \theta - R_t^{i,K})$. The previous equation defines the supply of loans to firms on areas with new investment opportunities. Notice that when $b_t = 0$, it boils down to a mark-up on the bank's net worth.

2.3.2 Banks on Areas Without New Investment Possibilities (*n*-Banks)

n-banks have an excess of liquidity as they have raised more deposits than loans demanded.

When choosing the supply of interbank credit, n-banks endogenize the probability that their counterparts default on the interbank loans. This happens if the realization of the shock on returns $x_{i,t}$ for borrowing banks is sufficiently small, i.e. such that the value of assets, net of deposits, is lower than outstanding interbank debt. As long as $x_{i,t} \in [0; h]$ borrowing banks are always solvent. On the contrary, if $x_{i,t} \in [-h; 0)$, borrowing banks may default. There is a critical value (a_t^i) of the shock $x_{i,t}$ below which a borrowing bank is insolvent on its interbank loans (i.e. $0 = (R_t^{i,K} + x_{i,t}) Q_t^i s_t^i + n_t^i - R_t^D d_t - R_t^B b_t$):

$$a_t^i = \frac{b_t^i R_t^B - n_t^i + R_t^D d_t}{Q_t^i s_t^i} - R_t^{i,K} + \varepsilon_t^a \tag{25}$$

with ε^a an exogenous confidence shock which follows an AR(1) process and has steady state of zero. Confidence shocks move the expectations of default on the interbank market despite fundamentals ($\frac{b_t^i R_t^B - n_t^i + R_t^D d_t}{Q_t^i s_t^i} - R_t^{i,K}$) remain unchanged. a is the limit value of the shock $x_{i,t}$ below which an interbank loan defaults (in this case the lending bank gets 0). The lower is a (i.e. the closer to $-h$) the larger needs a negative shock to be in order to trigger a default. If $x_{i,t} < a_t^i$, returns on loans are not sufficient for the borrowing bank to refund the entire sum borrowed plus interests. Intuitively, banks with larger net worth and higher average returns are more robust to adverse shocks (i.e. $x_{i,t}$ needs to be closer to $-h$ to induce a default). On the contrary, the more a bank is leveraged (so the higher its deposits and interbank loans are) the more a small shock can erode the net worth and lead to a default. a_t^i links the financial system and the real economy trough banks' choices. During booms, returns on capital increase, moving a closer to $+h$ and relaxing credit conditions on the interbank market. Lending banks supply more interbank credit and the total supply of retail loans is larger. Specularly,

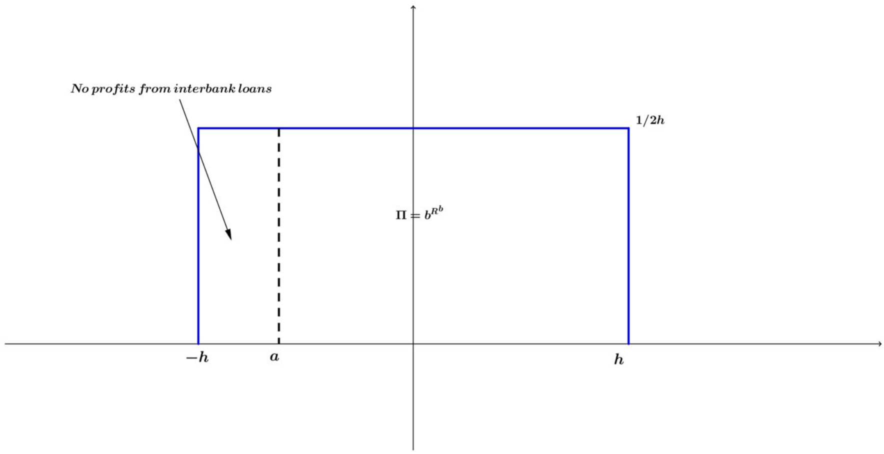

Fig. 3 Distribution of returns on interbank loans

during a crisis, borrowing banks adjust the amount of interbank credit extended in order to reduce exposure to risk. This decision diverts part of aggregate deposits from the supply of loan to the purchase of riskfree securities, reducing total credit available to firms and worsening the crisis (Fig. 3).

Effective (i.e. net of the probability of default) returns on interbank loans for an n-bank are defined by the payment distribution function:

$$\mathcal{F}_t = \frac{1}{2h}\int_{-h}^{a_t^i} 0 dx_{i,t} + \frac{1}{2h}\int_{a_t^i}^{h} R_t^B b_t dx_{i,t} \tag{26}$$

with end-of-period net worth being:

$$E_t n_{t+1}^n = n_t^n + R_t^{n,K}\psi_t Q_t^n s_t^n + \mathcal{F}_t + R_t^F f_t - R_t^D d_t \tag{27}$$

R^F is the riskless interest rate which equals the deposit rate. n-banks do not demand interbank loans, as those funds could be invested only in risk-free assets, see Proposition (2) in the Online Appendix. The objective function for n-banks is:

$$E_t \sum_{t=0}^{\infty} \Lambda_t^B n_{t+1}^n \tag{28}$$

which is optimized under the constraints of Eqs. (16) and (18). First order conditions are:

$$R_t^{n,K} - R_t^F = 0 \tag{29}$$

$$R_t^F - R_t^D = \frac{\lambda_t^n \theta}{\Lambda_t^B\left(1+\lambda_t^n\right)} \tag{30}$$

with $\{\lambda_t^n\}_{t=0}^{\infty}$ the sequence of Lagrangian multipliers associated to the problem. From the non-arbitrage condition follows that $\lambda_t^n = 0\ \forall t$. The supply of interbank loans is:

$$\frac{1}{2h}\left[R_t^B h - R_t^B a_t^i - b_t R_t^B \frac{R_t^B}{Q_t^i s_t^i}\right] - R_t^F = 0 \tag{31}$$

when optimally choosing the supply of interbank loans, n-banks take into account several factors. First, and most importantly, Eq. (31) depends on the probability of default on the interbank market. When it rises, expected returns on interbank credit decrease and banks shift liquidity from the interbank market to safe assets. That probability depends on the balance-sheet conditions of borrowing banks (which are i-banks) as well as from the state of the economy (through interest rates, returns on capital and credit demand, affecting the level of a). During downturns, for example, returns on capital decrease, the threshold a grows and the probability of default rises. This reduces the amount of interbank credit n-banks are willing to supply, worsening the crisis. Intuitively interbank credit also declines as the riskless interest rate grows which, in this model, is the opportunity cost of investing on the interbank market.

The probability of a default on the interbank market (δ) is the probability of the shock to fall in the interval $[-h; a_t^i]$:

$$\delta_t = \frac{1}{2h}\int_{-h}^{a_t^i} 1 dx_{i,t} = \frac{1}{2h}\left(a_t^i + h\right) \tag{32}$$

as $a_t^i \in [-h; 0)$, the probability of default increases as the dispersion of revenues increases. Notice also that the probability of default is defined by the financial conditions of debtor banks as well as by the state of the economy, through returns on capital $R^{i,K}$.

2.3.3 Aggregation

Banks operating on the same area can be aggregated as they face the same financial conditions (capital letters define aggregate variables). On n-areas the supply of loans to firms is:

$$S_t^n = \frac{1}{Q_t^n}\left(N_t^n + \pi^n D_t - B_t - F_t\right) \tag{33}$$

with, according to Eq. (11), $S_t^n = \pi^n (1 - \delta_K) K_t$ and $N_t^n = \pi^n N_t$. The total supply of interbank loans is:

$$B_t^* = \frac{Q_t^i S_t^i}{2h R_t^B}\left[R_t^B\left(h - a_t^i\right) - R_t^F\right] \tag{34}$$

on i-areas, the aggregate supply of retail loans is:

$$\tau_t^i N_t^i + \varpi_t^i B_t^* = \phi_t^i Q_t^i S_t^i \tag{35}$$

with, according to Eq. (11), $S_t^i = \pi^i (1-\delta_K) K_t + I_t$ and $N_t^i = \pi^i N_t$. As shown by Eqs. (35) and (34) the supply of loans on the interbank market defines the supply of final credit to firms on i-areas. At the end of the period, bank net worth is beginning-of-period net worth plus profit (or losses) from the banking activity. A fraction of banks, however, exits at the end of the period and is replaced by new banks, that receive an initial endowment of capital from households. Define N_{t-1}^o the end of period $t-1$ net worth of *surviving* banks and N_{t-1}^y the capital of new banks, banks net worth at the beginning of period t is:

$$N_t = N_{t-1}^o + N_{t-1}^y \tag{36}$$

the transfer from households to new banks is proportional to a fraction ξ of total loans intermediated (i.e. $N_{t-1}^y = \xi \left\{\pi^i \left[Z_t + (1-\delta_K) Q_t^i\right] S_t^i + \pi^n \left[Z_t^n + (1-\delta_K) Q_t^n\right] S_t^n\right\}$). Net worth of surviving banks is $N_t^o = \sigma \left(N_t^{o,i} + N_t^{o,n}\right)$. Net worth for i-banks is:

$$N_t^{o,i} = \frac{1}{2h}\int_{-h}^{a_t^i} 0 dx_{i,t} + \frac{1}{2h}\int_{a_t^i}^{h} \left[R_t^{i,K} + x_{i,t}\right] Q_t^i S_t^n dx_{i,t} + \pi^i N_t - \pi^i R_t^F D_t - R_t^B B_t \tag{37}$$

and for n-banks:

$$N_t^{o,n} = R_t^{n,k} Q_t^n S_t^n - \pi^n R_t^F D_t + \Pi_t^B + R_t^F F_t + \pi^n N_t \tag{38}$$

with $\Pi_{t-1}^B = \frac{1}{2h}\int_{-h}^{a_t^i} 0 dx_{i,t} + \frac{1}{2h}\int_{a_t^i}^{h} R_t^B B_t dx_{i,t}$.

At the beginning of each period, i-banks own $\pi^i N_t = N_t^i$ of total net worth and n-banks $\pi^n N_t = N_t^n$.

2.4 Equilibrium

In equilibrium production equals demand:

$$Y_t = C_t + I_t + G_t + \varepsilon_t^g \tag{39}$$

with ε^g a government spending shock that follows an AR(1) process. The total volume of riskless assets in the economy is the sum of deposits and risk-free securities acquired by banks:

$$D_t^T = D_t + F_t \tag{40}$$

Finally, total deposits are given by:

$$D_t = \sum_{h=i,n} (Q_t^h S_t^h - N_t^h) \tag{41}$$

while the central bank follows a linearized Taylor-type rule:

$$R_t^F = \psi_\pi \pi_t + \psi_y (Y_t - Y^{ss}) + \varepsilon_t^r \tag{42}$$

with ψ_π and ψ_y the sensitivity of monetary policy to inflation and output and ε^r a monetary policy shock that follows an AR(1) process.

3 Data

To estimate the model 5 key US quarterly macroeconomic variables are used: the log growth of real GDP, real consumption, real investment, interbank lending and the inflation rate. Data are related to the model thorough the following measurement equations:

$$\begin{bmatrix} dlGDP_t \\ dlCONS_t \\ dlINV_t \\ dlINT_t \\ dlP_t \end{bmatrix} = \begin{bmatrix} Y_t - Y_{t-1} \\ C_t - C_{t-1} \\ I_t - I_{t-1} \\ B_t - B_{t-1} \\ \pi_t \end{bmatrix}$$

All data are obtained from the US Department of Commerce—Bureau of Economic Analysis and cover the period 1977Q2-2018Q1. Real GDP is expressed in Billions of Chained 1996 US Dollars. Nominal Personal Consumption Expenditures, Fixed Private Domestic Investment and Interbank Loans are deflated by the US GDP-deflator. Variables are transformed in per-capita terms, de-trended and seasonally adjusted following Smets and Wouters (2003) and Smets and Wouters (2007).

4 Bayesian Estimation

The log-linearized version of the model can be written in state-space form. Following Gerali et al. (2010) and Darracq Paries et al. (2011), only a subset of the deep parameters of the model are estimated. As in those settings, parameters defining preferences and the production function are estimated while depreciation rates and demand elasticities are calibrated. This approach has the advantage of building on the (micro) empirical literature for those parameters.

The households discount factor β is calibrated to 0.99. Capital depreciation δ^K is set to 0.025 while, following the estimates of Gertler and Kiyotaki (2010), π^i is set to 0.25. The steady state default rate on the interbank market is set to 0.003 according to the long run average provided by Moody's[26] while the variance of returns on investment projects h is set to 0.5 following the calibration proposed by Angeloni and Faia (2009) that is based on the empirical findings of Bloom et al. (2018). This parameter captures the dispersion of returns. In Bloom et al. (2018) it is estimated using industry-level data; given the micro-database used, it is preferable and more robust to calibrate this parameter based on those results rather than trying to recover it from an aggregate volatility index that would also require a second or third order solution of the model. ν is set to 0.6 following Gertler and Kiyotaki (2010). σ, the surviving probability of banks, is set to 0.972 leading to an average surviving time of 10 years. The steady state ration of $\frac{C}{Y}$, $\frac{I}{Y}$ and $\frac{G}{Y}$ are calibrated to 0.62, 0.18 and 0.2 respectively. θ is set to

[26] For more details see Moody's (2009).

0.129 as in Gertler and Kiyotaki (2010) and the Calvo parameter θ_R to 0.75 following the New-Keynesian literature.

The remaining deep parameters of the model are estimated following Smets and Wouters (2007). The posterior distribution of the model's parameters Ψ is approximated to the likelihood times the prior distribution, according to the well-known relation:

$$p\,(\Psi \mid Y) \propto \mathcal{L}\,(Y \mid \Psi)\, p\,(\Psi) \tag{43}$$

with $\Psi = [\sigma^{\varepsilon^e}, \sigma^{\varepsilon^A}, \sigma^{\varepsilon^a}, \sigma^{\varepsilon^r}, \sigma^{\varepsilon^g}, \rho_e, \rho_A, \rho_a, \rho_r, \rho_g, \alpha, \varphi, \varepsilon, f, \theta, \theta_R, \psi_y, \psi_\pi]^T$. Given that does not exist a closed form solution for Eq. (43), the equation is evaluated with a MCMC algorithm repeated for 2 chains with 1 million draws each.

4.1 Prior Choices

Following Smets and Wouters (2007), the standard deviations of shock processes are assumed to follow an inverse gamma distribution with mean 0.01 and a standard deviation of 2. A beta distribution is used for the autoregressive components of the shock processes with mean 0.5 and a standard error of 0.2. The technology parameter α is assumed to follow a beta distribution with mean 0.33 and a 0.05 standard deviation.

The parameters of the utility function, φ and ε, follow a beta distribution with mean 0.5 and 0.1 and standard errors of 0.1 and 0.01. f follows a beta distribution with mean 0.25 and standard error of 0.1. The mean for f is chosen according to Bernanke et al. (1999). Finally the two policy parameters have a gamma distribution with mean 0.8 and 1.5 and standard deviations of 0.2 and 0.5 respectively.[27]

4.2 Estimation Results

Estimation results are reported in Table 2. Results are generally in line with the literature. The sensitivity of the policy function to inflation is larger than to output; technology and preference parameters are similar to estimates provided in other paper; the autocorrelation coefficients are high similar to Smets and Wouters (2003) and Smets and Wouters (2007).

Surprisingly, f, the parameter associated with the log-linearized Tobin's Q equation, is much lower than what calibrated by Bernanke et al. (1999). To verify the robustness of the estimation two standard tests for the identification of DSGE models are implemented. First, following Andrle (2010) and Iskrev and Ratto (2011), it is tested whether the likelihood function has sufficient curvature in the direction of the parameters; second a singular value decomposition is used to verify the identification of the parameters.[28] Results are reported in Figures C.III-C.VI of the Online Appendix C. Overall, these robustness checks deliver three main conclusions: (i) there are not unidentified parameters in the model, (ii) the parameter f appears to be well identified, (iii) the variance of the exogenous shocks is correctly identified as well.

[27] An alternative approach would be to use macro-priors following Lombardi and Nicoletti (2012); in this case the standard approach is used which is also consistent with the variables selected.

[28] See Online Appendix B.5 for a complete derivation.

Table 2 Estimated parameters

Parameter	Name	Prior shape	Prior mean	Post. st. dev.	Post. mean	10%	90%
σ^{ε_e}	Std. pref. shock	Γ^{-1}	0.01	2	15.6631	7.1084	24.1765
σ^{ε_A}	Std. TFP shock	Γ^{-1}	0.01	2	5.9798	2.9871	8.8270
σ^{ε_d}	Std. risk shock	Γ^{-1}	0.01	2	22.3271	19.9628	24.6378
σ^{ε_r}	Std. mon. policy shock	Γ^{-1}	0.01	2	1.1123	0.6661	1.5642
σ^{ε_g}	Std. gov. spending shock	Γ^{-1}	0.01	2	2.6648	2.4200	2.9009
ρ_e	Autocorr. pref. shock	β	0.5	0.2	0.9960	0.9929	0.9992
ρ_A	Autocorr. TFP shock	β	0.5	0.2	0.9875	0.9806	0.9947
ρ_d	Autocorr. risk shock	β	0.5	0.2	0.9843	0.9722	0.9967
ρ_r	Autocorr. mon. policy shock	β	0.5	0.2	0.9623	0.9384	0.9876
ρ_g	Autocorr. gov. spendig shock	β	0.5	0.2	0.9936	0.9888	0.9987
α	Capital share	β	0.33	0.05	0.3788	0.2996	0.4571
φ	Habit param	β	0.5	0.1	0.7420	0.6810	0.8043
ε	Inverse of Frish elasticity of labor	β	0.1	0.01	0.1007	0.0842	0.1172
f	Elasticity of Q	β	0.25	0.1	0.0385	0.0230	0.0540
ψ_y	Response to output	Γ	0.8	0.2	0.2456	0.1346	0.3527
ψ_π	Response to inflation	Γ	1.5	0.5	2.5746	1.5167	3.5706

There is a last source of concern for the estimation results: the non-linearities generated in the data by the effective lower bound (ELB) and the global financial crisis. Data on the post-ELB period represent a small part of the sample and, therefore, they should not significantly bias the result. As a robustness test, however, the model has been estimated excluding the ELB and post-ELB period (i.e. truncating the sample in 2008Q1). Results are reported in the Online Appendix D where impulse responses are shown to be relatively stable, with overlapping 90% confidence intervals around responses.[29]

5 Shock Responses

This section discusses the responses of key variables to exogenous shocks.[30]

This model features an highly complex interbank market, where counterparty risk is directly taken into account by bankers when issuing interbank credit and, through that, it affects the supply of final credit and total output. As borrowing banks become less resilient, expected returns on interbank credit fall (as the default probability rises); when that happens, bankers move excess liquidity away from the interbank market and invest in riskless assets. This mechanism adds an important—micro-founded—risk channel to existing business cycle dynamics whiche reinforces the impact and the persistence of shocks. For example, consider the case of a negative TFP shock: returns on capital ($R^{i,K}$) decrease and a_t^i moves to the right (Eq. (25)). That increases the "zero profit area" for banks supplying credit on the interbank market, Eq. (26), reducing the amount of funds they allocate on the interbank market; the supply of final credit in i-areas contracts; as a consequence, valuable investment projects do not start, lowering output and worsening the crisis.

Turning to specific IRFs a positive productivity shock, Fig. 4, boosts output and increases inflation in the medium term even if, on impact, inflation declines due to the decrease in the hours worked and the consequent change of the mark-up. The central bank reacts accordingly, decreasing the interest rate in the first periods (the sensitivity to inflation is higher that that to output in the Taylor rule) and increasing it later on when inflation picks up. The price of capital also increases. On the interbank market, the increase of average returns boosts loans to firms on both areas. This is due to the reduction of the default probability on the interbank market (i.e. a_t^i moves to the left) which induces n-banks to supply more interbank credit which turns into more final loans on i-areas.

Profitability for i-banks rises (as they can issue more loans) while profits fall (driven by the reduction of both the risk-free and interbank interest rates) for n-banks. As n-banks are more than i-banks, the aggregate net worth decreases. The overall probability of default decreases driven by the higher returns on capital $R^{i,K}$ and stronger capital for i-banks. Improved financial conditions also lead to more investments and higher output.

[29] For the truncaed sample, the MCMC algorithm needs 2 million draws to converge, so each chain has 2 million iterations.

[30] Full IRFs for all variables and shocks are reported in the Online Appendix C.

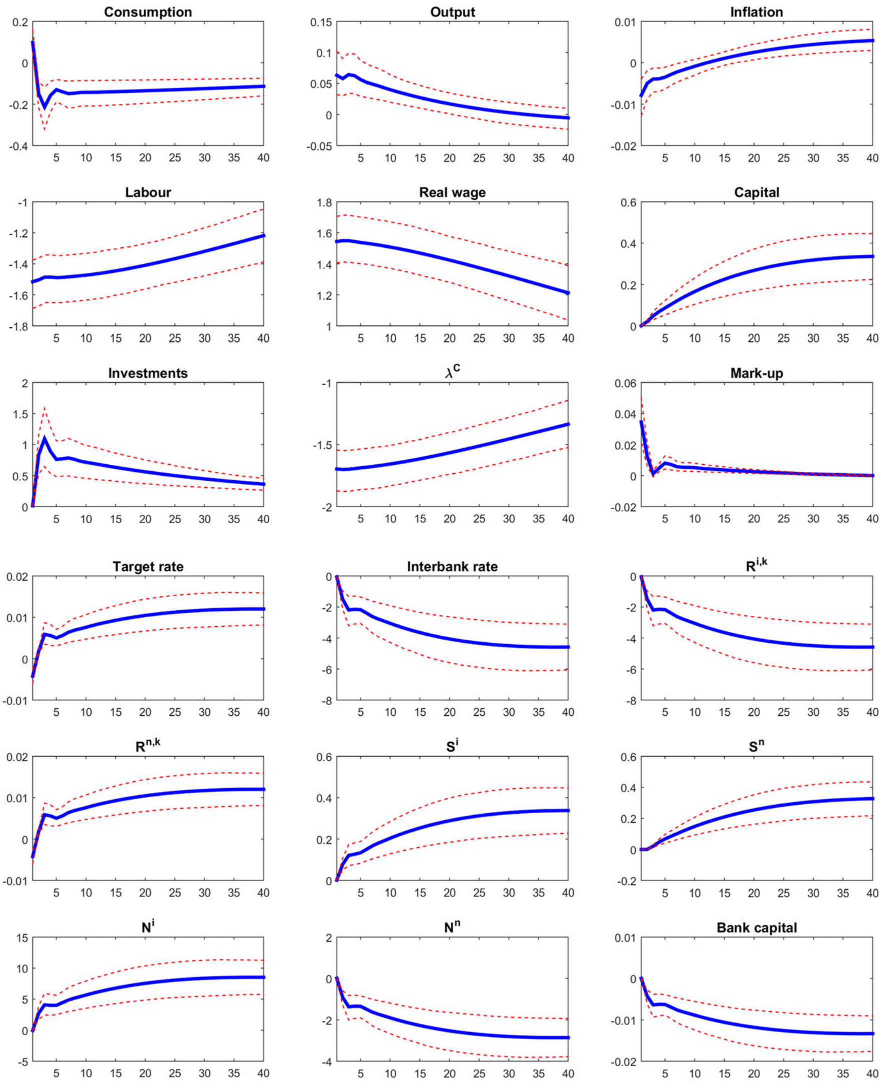

Fig. 4 Orthogonal shock to A. Notes: standardized IRFs (solid line) with 90% confidence intervals (dashed line)

The responses to a consumers' preference shock and a government spending shock are broadly standard.[31] A negative consumers' preference shock decreases the marginal value of consumption (λ^C). Total demand falls as investments do not rise enough to compensate for the fall in consumption. At the same time real wages go up increasing the real marginal cost and putting upward pressures to inflation. A government spending shock boosts output and consumption while decreases investments.

31 See Figures C.IX and C.VIII of the Online Appendix C.

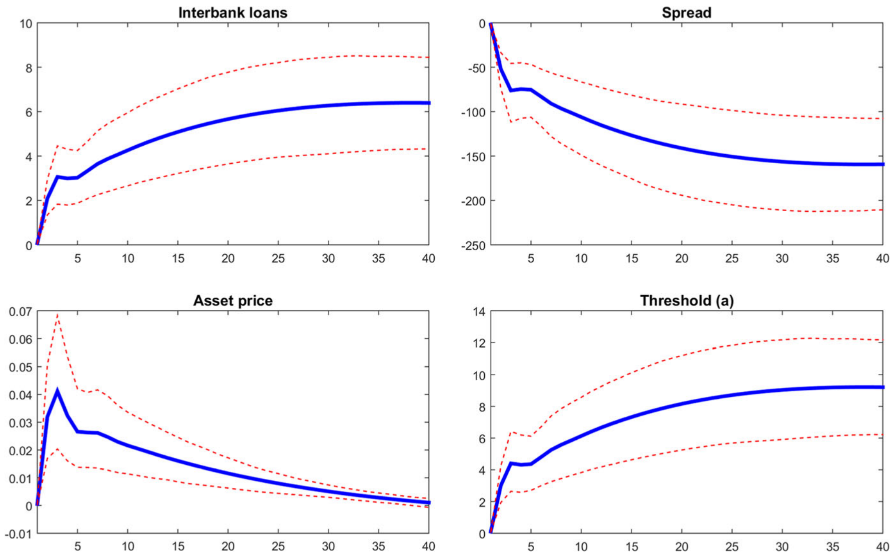

Fig. 4 continued

The key shock in this model is the confidence shock, i.e. a shock to a_t^i which defines the risk of extending interbank credit. It can be interpreted as an increase in the expectation of default of interbank loans not justify by fundamentals stemming from a loss in trust between financial. That translates in a contraction of interbank credit (as expected interbank returns decrease) and retail loans which generate a slowdown in output and a recession. Responses to a 1% exogenous increase in ε_t^a are reported in Fig. 5. a_t^i increases as it moves closer to $+h$, so that less negative realizations of x—the investment returns stochastic component—can trigger a default. The "zero profits" area of Eq. (26) grows and reduces expected interbank credit returns. The supply of interbank loans contracts as n-banks divert resources from the interbank market to riskless assets. Firms on i-areas have access to less credit, lowering investments and contracting output. Firms' capital (K) drops—recall that entrepreneurs are penniless—and inflation rises as the marginal cost increases (i.e. firms are forced to produce using a less efficient combination of inputs). Finally banks' net worth decreases; this translates into a more fragile banking system in the following periods. At the same time, as inflation raises the central does not cut interest rates aggressively enough. Banks are more fragile, with less capital and higher financing rates; as the economy has entered a recession, also returns on capital on i areas ($R^{i,K}$) are lower. All those factors add up and make interbank credit more risky in light of weaker capital of borrowing banks and lower profitability for new investments; n-banks invest a larger share of their excess liquidity on risk-free assets. The mechanism is self reinforcing and expectations of banks (which triggered the crisis in the first place) are self-fulfilling. If the shock is sufficiently large, it can completely freeze the interbank market, similarly to the experience of 2008. These effects are also quantitatively large: a 1% increase in a_t^i would contract GDP by 1.5 bp and investments by 50 bp. During the GFC the

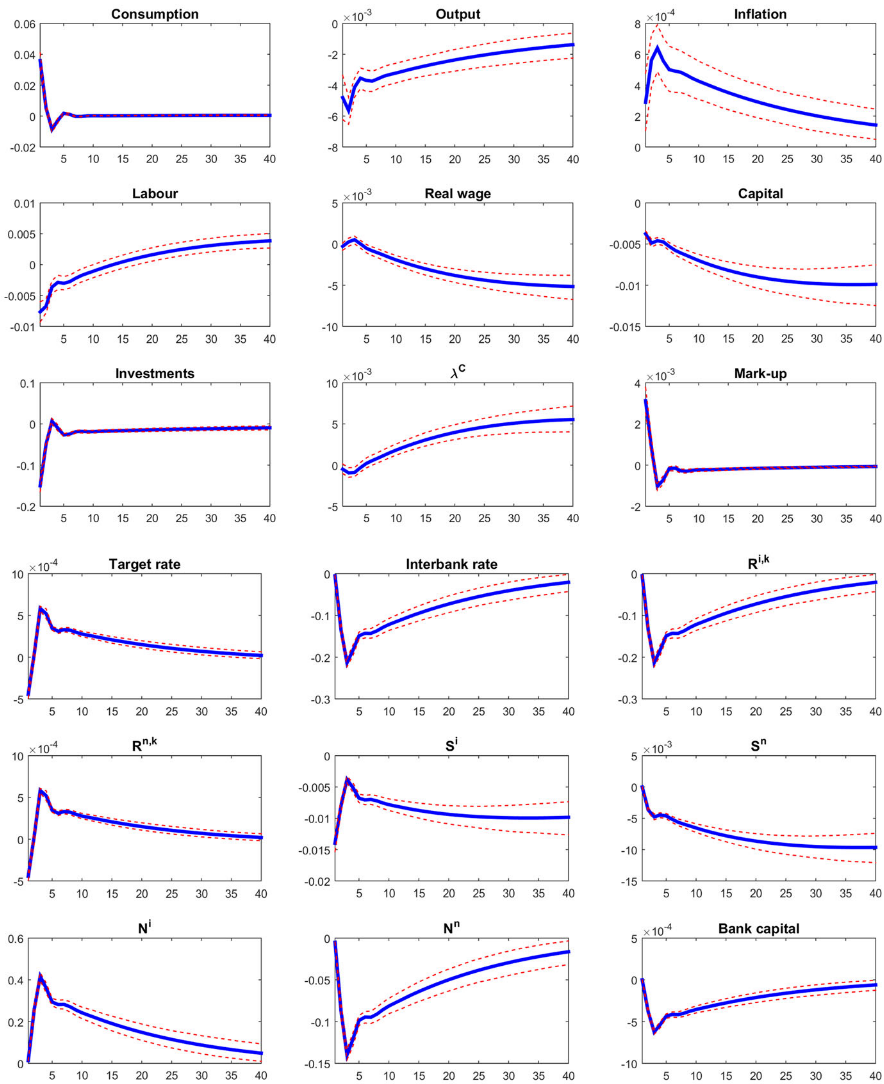

Fig. 5 Orthogonal shock to a_t^i. Notes: standardized IRFs (solid line) with 90% confidence intervals (dashed line)

VIX, a standard measure of risk, increased by 400% compared to its long run average, see Fig. 6; even if this is simply a real-world proxy for a_t^i, the effects of confidence shocks on real variables appear to be sizable.

The monetary authority, additionally, is ineffective in counteracting such a shock for two reasons: first, inflation rises as firms produce with an inefficient combination of inputs forcing the central bank, according to the Taylor rule, to increase the policy rate in the medium term; second, the initial easing is ineffective in preventing the crisis as the target rate moves only marginally a_t^i and the default probability on

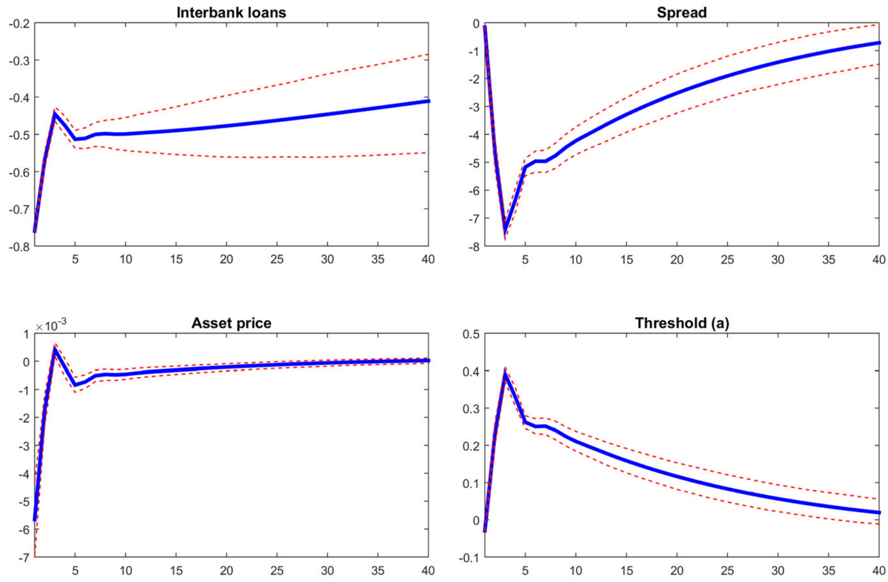

Fig. 5 continued

Fig. 6 The Vix in 2007 and 2008. Notes: Vix during 2007 and 2008 compared to its long run mean. Sources: Chicago Board Options Exchange

the interbank market. This experiment highlights the—complex—interaction between interbank risk and the real economy. When the risk of default is perceived to be higher, banks withdraw funds from the interbank market to invest in risk-free assets. Despite being rational for the individual bank, this behavior has severe consequences for the economy as it limits the credit availabile to firms. These simulations also endogenously generates a "credit crunch" following a negative confidence shock, rationalizing the behavior banks during the GFC and highlighting the channel through which it affects the real economy.

Finally a (positive) monetary policy shock slightly increases λ^C leading to a small increase in consumption that, however, dies out quickly.[32] As in standard New-Keynesian literature it reduces output and inflation. On top of standard demand-supply dynamics in this model there is an additional transmission channel for monetary policy. When the target rate increases, returns on risk-free assets rise. As risk-free assets become more attractive, n-banks change the composition of their balance sheet, reducing interbank credit. Liquidity constraints for i-banks become more binding and final credit drops, leading to a reduction of investments and a decrease in the capital stock (K). As the economy enters a moderate recession, returns on capital $R^{h,K}$ decrease making interbank credit more risky and reinforcing the credit crunch. This channel builds on top of the previously discussed dynamics. Overall, the risk-channel has a multiplying effect in downturns as, on top of the slowdown in demand, it generates a contraction of credit: interbank loans become more risky and funds do not flow to banks with valuable investment projects to finance. Notably, also, its effects are long lasting through banks' net worth.

6 Conclusions

This model integrates into a standard DSGE model with frictions a complex interbank market. The economy is populated by banks that are financially constrained and face shock to the loan demand in each period. This generates a national interbank market where banks with excess of funds can finance banks which have access to valuable investment projects but have no funds to finance them. However credit is risky and banks can decide to invest excess liquidity also in risk-free assets that generate lower returns but without risk. When deciding how to invest excess liquidity, banks take explicitly into account the likelihood that their counterparts on the interbank market default adjusting the supply of interbank loans accordingly (i.e. they extend interbank loans as long as expected returns on interbank credit equal the riskless rate). The default probability is fully micro-founded and depends on aggregate credit conditions (i.e. returns on investments, cost of funding) as well a on the state of the banking system (i.e. the capitalization of banks). The mechanism has a multiplicative effect: bank credit is necessary to production therefore if banks reduce the credit supply firms are forced to scale down production or increase prices.[33]

This model also allows to explicitly assess the role of counterparty risk, defined as the probability that a banks defaults on its interbank liabilities. When counterparty risk is (perceived to be) higher, banks re-optimized their asset allocation, diverting funds from the interbank market to invest in riskless assets. Doing so, they generate a "credit crunch" reducing the amount of funds available to finance final loans to firms and, therefore, leading to a contraction in output. These effects are qualitatively and quantitatively significant as an increase of counterparty risk by 1% generates a drop of 1.5 bp in output and 50 bp in investments. This channel explains how a freezing

32 These IRFs are reported in in Figure C.VII in the Online Appendix C.

33 Firms may maintain the same level of production substituting capital with labor. This, however, increases the marginal cost of production and therefore prices as the combination of inputs is less efficient.

of the interbank market generates a real recession. In those cases standard monetary policy is ineffective. In fact, after pure riskiness shock a standard Taylor principle can be counter-effective as central banks (overly) react to inflation, increasing the opportunity costs of interbank credit.

In conclusion, this paper shows the complex interactions that exists between financial markets and the real economy. Financial agents, optimize their portfolio taking into account counterparty risk, especially during contractions. Doing so, downturns are more severe as the fall in credit leads to stronger contractions of output. During crises, banks fly to safety investing relatively more on riskless asset, reducing the amount of funds available to issue final loans to firms that (implicitly) sustain investments and aggregate demand. This mechanism rationalizes the behavior of banks during the GFC, explaining their decisions and highlighting the channel through which that had an impact on the real economy. A standard Taylor principle seems adequate to counterbalance real shocks while it presents some limits when it comes to pure financial shocks. In particular, in the case of shocks to risk, the application of the Taylor principle may even worsen the crisis.

One possible extension of the paper could be indeed to study if unconventional monetary policies can counteract a risk crisis when conventional measures are ineffective. One way to model unconventional policies in this economy could be to follow Gertler and Karadi (2011) or to apply in a closed economy setting the policies presented by Dedola et al. (2013).

References

Affinito M, Piazza M (2018) Always look on the bright side? central counterparties and interbank markets during the financial crisis. Bank of Italy, Temi di Discussione, p 1181

Affinito M, Pozzolo AF (2017) The interbank market network across the global financial crisis: evidence from Italy. J Bank Finance 80(C):90–107

Albertazzi U, Angelini P, Columba F, Cornacchia W, Di Cesare A, Panetta F, Pilati A, Santini G, Salleo C (2009) Financial sector pro-cyclicality: lessons form the crisis. Questioni di Economia e Finanza (Occasional Papers Bank of Italy)

Allen F, Babus A, Carletti E (2009) Financial crises: theory and evidence. Annu Rev Financ Econ 1(1):97–116

Allen F, Gale D (2000) Financial contagion. J Political Econ 108(1):1–33

Andrle M (2010) A note on identification patterns in dsge models, European Central Bank Working Papers Series (1235)

Angelini P, Nobili A, Picillo C (2011) The interbank market after august 2007: what has changed and why? J Money Credit Bank 43(5):923–958

Angeloni I, Faia E (2009) A tale of two policies: prudential regulation and monetary policy with fragile banks. Kiel Working Papers (1569)

Archarya VV, Gale D, Yorulmazer T (2011) Rollover risk and market freezes. J Finance 66(4):1177–1209

Archarya VV, Skeie D (2011) A model of liquidity hoarding and term premia in inter-bank markets. J Monet Econ 58(5):436–447

Bargigli L, di Iasio G, Infante L, Lillo F, Pierobon F (2015) The multiplex structure of interbank networks. Quant Finance 15(4):673–691

Barone G, de Blasio G, Mocetti S (2016) The real effects of credit crunch in the great recession: evidence from Italian provinces. Reg Sci Urban Econ 70(C):352–359

Becker B, Ivashina V (2014) Cyclicality of credit supply: firm level evidence. J Monet Econ 62(C):76–93

Bernanke B, Gertler M, Gilchrist S (1999) The financial accelerator in a quantitative business cycle framework. Handb Macroecon 1(1):1341–1393

Bias B, Heider F, Hoerova M (2016) Risk sharing or risk taking? Counterparty risk, incentives, and margins. J Finance 71(4):1669–1698
Bloom N, Floetotto M, Jaimovich N, Eksten IS, Terry S (2018) Really uncertain business cycles. Econometrica 86(3):1031–1065
Boissay F, Collard F, Smets F (2016) Booms and banking crises. J Political Econ 124(2):489–538
Branch WA, Evans GW (2005) Intrinsic heterogeneity in expectation formation. J Econ Theory 127(1):264–295
Brunnermeier MK (2009) Deciphering the liquidity and credit crunch 2007–2008. J Econ Perspect 23(1):77–100
Brunnermeier M, Sunnikov Y (2014) A macroeconomic model with a financial sector. Am Econ Rev 104(2):379–421
Calvo GA (1983) Staggered prices in a utility-maximizing framework. J Monet Econ 12(3):383–398
Carrera C, Vega H (2012) Interbank market and macroprudential tools in a dsge model. Working Papers Banco Central de Reserva del Perù 12
Cignano F, Manaresi F, Sette E (2016) Does credit crunch investment down? new evidence on the real effects of the bank-lending channel. Rev Financ Stud 29(10):2737–2773
Darracq Paries M, Sorensen CK, Rodriguez-Palenzuela D (2011) Macroeconomic propagation under different regulatory regimes: Evidence from an estimated dsge model for the euro area. Int J Cent Bank 7(4):49–113
de Grave F, Dossche M, Emiris M, Sneessens H, Wouters R (2010) Risk premium and macroeconomic dynamics in a heterogeneous agent model. J Econ Dyn Control 34(9):1680–1699
De Socio A (2013) The interbank market after the financial turmoil: squeezing liquidity in a "lemon market" or asking liquidity "on tap". J Bank Finance 37(5):1340–1358
Dedola L, Karadi P, Lombardi G (2013) Global implications of national unconventional policies. J Monet Econ 60(1):66–85
Delli Gatti D (2012) The long crisis, UCSC Lecture
Delli Gatti D, Longaretti R (2006) The non-superneutrality of money and its distributional effects when agents are heterogeneous and capital markets are imperfect. UNIMIB Working Papers (95)
Diamond DW, Rajan RD (2001) Liquidity risk, liquidity creation and financial fragility: a theory of banking. J Political Econ 109(2):287–327
Dib A (2010) Banks, credit market frictions and business cycles, Bank of Canada Working Papers, pp 10–24
Diebold FX, Yilmaz K (2009) Measuring financial asset return and volatility spillovers, with application to global equity markets. Econ J 119(534):158–171
Dixit A, Stiglitz J (1977) Monopolistic competition and optimum product diversity. Am Econ Rev 67(3):297–308
Eisenberg L, Noe TH (2001) Systemic risk in financial systems. Manag Sci 47(5):205–336
Fostel A, Geanakoplos J (2009) Leverage cycles and the anxious economy. Am Econ Rev 98(4):1211–44
Gai P, Kapadia S (2010) Contagion in financial networks. Proc R Soc Lond A Math Phys Eng Sci 466(2120):1211–44
Gerali A, Neri S, Sessa L, Signoretti FM (2010) Credit and banking in a DSGE model of the euro area. J Money Credit Bank 42(s1):107–141
Gertler M, Karadi P (2011) A model of unconventional monetary policy. J Monet Econ 58(1):17–34
Gertler M, Kiyotaki N (2010) Handbook of monetary economics, vol 3, 1 edn, Elsevier, chapter, Financial intermediation and credit policy in business cycle analysis
Gertler M, Kiyotaki N (2015) Banking, liquidity and bank runs in an infinite horizon economy. Am Econ Rev 105(7):2011–43
Gertler M, Kiyotaki N, Prestipino A (2016) Handbook of macroeconomics, vol 2, Elsevier, chapter Wholesale banking and bank runs in macroeconomic modeling of financial crises, pp 1345–1425
Giri F (2018) Does interbank market matter for business cycle fluctuation? An estimated dsge model with financial frictions. Econ Model 75:10–22
Goodhart C, Tsomocos D (2009) Default and DSGE models, VOX EU
Gorton G (2009) Slapped in face by the invisible hand: the Panico of 2007. Oxford University Press, Oxford
Guillen MF (2011) The global economic and financial crisis: a timeline, The Lauder Institute Working Papers
Haldane AG, May RM (2011) Systemic risk in banking ecosustems. Nature 469:351–355
Heider F, Hoerova M, Holthausen C (2015) Liquidity hoarding and interbank market spreads, the role of counterparty risk. J Financ Econ 118(2):336–354

Hilberg B, Hollmayr J (2011) Asset prices, collateral and unconventional monetary policy in a DSGE model, European Central Bank Working Papers Series (1373)

Hommes CH (2006) Handbook of computational economics, vol 2, Elsevier, chapter heterogeneous agents models in economics and finance

Hong Y, Liu Y, Wang S (2009) Granger causality in risk and detection of extreme risk spillover between financial markets. J Econ 150(2):271–287

Iskrev N (2010) Evaluating the strength of identification in DSGE models. an a priori approach, Society for Economic Dynamics, 2010 Meeting Papers (1117)

Iskrev N, Ratto M (2011) Algorithms for identification analysis under the dynare environment: final version of the software, Joint Research Center European Commission

Iyer R, Peydrò J-L (2011) Interbank contagion at work: evidence from a natural experiment. Rev Financ Stud 24(4):1337–1377

Iyer R, Peydrò J-L, da Rocha Lopes S, Schoar A (2014) Interbank liquidity crunch and the firm credit crunch: evidence from the 2007–2009. Rev Financ Stud 27(1):347–372

Jimènez G, Ongena S, Peydrò J-L, Saurina J (2014) Hazardous times for monetary policy: what do twenty-three million bank loans say about the effects of monetary policy on credit risk-taking? Econometrica 82(2):463–505

Jorion P, Zhang G (2009) Credit contagion from counterparty risk. J Finance 64(5):2053–2087

Kiyotaki N, Moore J (1997) Credit cycles. J Political Econ 105(2):211–248

Krishnamurthy A (2003) Collateral constraints and the amplification mechanism. J Econ Theory 111(2):277–292

Lombardi M, Nicoletti G (2012) Bayesian prior elicitation in DSGE models: macro- vs micropriors. J Econ Dyn Control 36(2):294–313

Meeks R, Nelson B, Alessandri P (2017) Shadow banking and macroeconomic instability. J Money Credit Bank 49(7):1483–1516

Moody's (2009) Corporate default and recovery rates, 1920–2008, Moody's Global Credit Policy

Motta G, Tirelli P (2015) Money targeting, heterogeneous angents and dynamic instability. Macroecon Dyn 19(2):288–310

Phelan C, Townsend RM (1991) Computing multi-period, information-constrained optima. Rev Econ Stud 58(5):853–881

Smets F, Wouters R (2003) An estimated dynamic stochastic general equilibrium model of the euro area. J Eur Econ Assoc 1(5):1123–1175

Smets F, Wouters R (2007) Shocks and frictions in us business cycles: a bayesian DSGE approach. Am Econ Rev 97(3):586–606

Stiglitz JE, Greenwald B (2003) Towards a new paradigm in monetary economics. Cambridge University Press, Cambridge

Takamura T (2013) A general equilibrium model with banks and default on loans. Bank of Canada Staff Working Papers , vol 13, no 3

Vasso I, Onegena S, Peydrò J-L (2015) Monetary policy, risk-taking and pricing: evidence from a quasi-natural experiment. Rev Finance 18(1):95–144

Xuewen L (2016) Interbank market freezes and creditor runs. Rev Financ Stud 29(7):1860–1910