Assortative Matching, Interbank Markets, and Monetary Policy[†]

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Abstract

We develop a quantitative macroeconomic framework with heterogeneous financial intermediaries and active liquidity management. In the model, banks manage uninsured, idiosyncratic deposit withdrawal risk through an iterative over-the-counter interbank market, which generates a network-like structure with endogenous intensive and extensive margins and results in equilibrium assortative matching based on balance sheet size. We validate our framework using administrative data from Germany that encompasses the entire universe of bank-to-bank loan exposures. Our findings strongly support the presence of assortative matching in the data, thereby confirming the model's key mechanism. We show that assortative matching is inefficient: it leads to reduced trading volumes and a broader region of inaction in the interbank market, a smaller and riskier banking sector, and a macroeconomy that is characterized by lower aggregate output and consumption. Using our empirically validated framework, we explore secular trends in interbank trading, the roles of liquidity and interest rate corridor policies, and the impact of deposit market power.

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1 Introduction

This paper studies the bank lending channel of monetary policy transmission in an environment where heterogeneous banks manage their liquidity under a dynamic interest rate corridor rule and a frictional interbank market. The combination of bank heterogeneity and interbank market frictions yields novel theoretical and policy-relevant conclusions that are supported and validated by administrative micro data from Germany.

Theoretically, we build on the influential contribution of Bianchi and Bigio (2022) who develop a rich theory of banks' liquidity management and the credit channel of monetary policy transmission. We study a micro-founded general equilibrium model where heterogeneous financial intermediaries face uninsured idiosyncratic deposit withdrawal risk and a binding minimum reserve requirement rule. Banks can manage this liquidity problem by tapping into the interbank market. The monetary authority controls the interest rate corridor—the main refinancing rate, the deposit facility rate, and the lending facility rate. Banks make intertemporal lending and deposit sourcing decisions, which in turn affect firm production, aggregate output, and consumption. Interbank market frictions have first-order effects on the macroeconomy through the interplay between banks' liquidity management problem and endogenous size heterogeneity.

There are two critical aspects of our framework. First, the model generates *assortative matching* in the interbank market: big banks tend to lend to and borrow from other big banks. This theoretical prediction is strongly supported by our micro data. Second, there is *equilibrium rationing* in the interbank market. Our solution approach gives precedence to large and efficient intermediaries based on a "first-come first-serve" logic: small, inefficient banks get to solve the liquidity management problem last, and by the time their turn arrives there may be no counterparties left. Those who are left out must turn to the lender of last resort and borrow at a penalty rate, as per the interest rate corridor regime.

Our solution algorithm for the interbank market is by itself a stand-alone contribution of the paper. The algorithm is loosely related to the approach of settling the firm entry problem in Atkeson and Burstein (2008). The number of banks in the economy is discrete. Banks are ex-ante heterogeneous in monitory efficiency (Stiglitz and Weiss, 1981), which in equilibrium yields a positive correlation between efficiency and size. Uninsured idiosyncratic deposit withdrawal shocks generate banks with deficit and excess reserves. When the interbank market opens, we assume that banks make portfolio choice decisions in order, which is determined by their efficiency-size profile. The largest and most efficient borrower with a deficit in reserves moves first. The borrower goes down the pecking order of lenders according to their own efficiency level. There are variable and fixed costs of match formation. Importantly, variables costs are *match-specific*, making sorting and assortative matching more likely to occur in equilibrium. The borrower makes the decision of how much and whether to borrow from each lender depending on the outside option: the lending facility. Because the lending facility comes with a penalty, the borrower would always in principle prefer to borrow through the interbank market. However, costly match formation can yield inefficient outcomes for both sides. In the end, there could be rationing of *both* borrowers and lenders: a number of unlucky borrowers could be too far down in the pecking order. Those would be forced to borrow at the penalty rate. In the meantime, any rationed-out lenders would turn to their second-best option: the deposit facility of the central bank, which lends at a discount relative to the interbank market. In addition to assortative matching in the interbank market, the model predicts a positive association between interbank volumes and balance sheet size (e.g. total assets or total net worth).

An important additional testable prediction of our model is that in response to contractionary monetary policy shocks - which constitute policy rate hikes and widenings of the interest rate corridor spread - the interbank market expands while the real economy shrinks. A higher refinancing rate raises the banks' cost of liabilities because of the perfect pass-through onto retail deposit rates, leading to a decline in deposit sourcing, less lending to non-financial firms, and a decline in aggregate production and consumption. At the same time, a wider corridor spread increases the lending facility rate everything else equal. The outside option for borrowers in the interbank market is less attractive, which causes an expansion in the interbank market along the intensive and extensive margins.

Empirically, we provide extensive validation of our testable predictions and model mechanisms. For this purpose, we leverage the quarterly administrative credit registry from Germany that spans the period from 2002 to 2019 and covers, on average, 1,800 banks and 28,251 interbank connections per quarter. We document several important facts. First, there is strong empirical evidence in favor of both assortative matching and rationing out in the German interbank market. Second, there is a positive correlation between interbank market volume and bank balance sheet size. Third, following identified contractionary shocks to the ECB policy rate, German banks *increase* the amount of lending and the number of connections in the interbank market. Fourth and finally, we identify significant heterogeneous effects that suggest that assortative matching strengthens following positive interest rate shocks, in line with our model. Thus, our empirical analysis strongly supports the model's main mechanisms along the cross-sectional and dynamic dimensions.

We then use our empirically validated model to run several quantitative experiments.

First, we use our model to match the secular decline in interbank lending in Germany over the past 20 years. We target the linear trend in the trading volume and reverse-engineer the path of structural parameters than can produce the path of volume that matches the data. Importantly, the model also predicts an empirically-realistic decline in the extensive margin, which is an untargeted moment. Second, we study the impact of liquidity policies by simulating transitory changes in the minimum reserves requirement. Our model predicts that tightening reserve requirements improves financial stability by lowering the leverage ratio but reduces efficiency as banks hold a greater buffer stock of reserves instead of lending those funds to non-financial firms. Third and finally, we depart from the baseline assumption of perfect banking competition and introduce bank market power into the deposit market - a salient feature of the German banking industry. We find that deposit market power - in combination with bank heterogeneity and an active interbank market - comes with considerable implications for interbank-market activities, the financial sector more broadly, and the macroeconomy.

Overall, since our framework is thoroughly validated with cross-sectional and conditional tests, we argue that results that come out from our quantitative experiments are noteworthy. A model that generates realistic behavior in the steady state and along transition paths following interest rate shocks is likely to have equally realistic and correct predictions in other circumstances as well. For example, model predictions with respect to liquidity policy shocks can be useful for policy-makers, considering that such shocks are hard to identify in the data.

Literature Our paper relates to several distinct strands of the literature. First, a burgeoning literature introduces heterogeneity in the financial sector of canonical macro-banking frameworks. Notable contributions include Corbae and D'Erasmo (2021); Elenev et al. (2021); Begenau and Landvoigt (2022); Coimbra and Rey (2023); Bellifemine et al. (2023). In particular, our framework is most closely related to Jamilov and Monacelli (2023) but introduces a non-trivial interbank market and endogenous liquidity management. In its stripped-down version, our model can nest the canonical Gertler and Kiyotaki (2010); Gertler and Karadi (2011) macro-banking model with a representative intermediary as a special case.

Second, our paper relates more generally to the literature on monetary policy transmission and banks' liquidity management (Poole, 2017; Keister and McAndrews, 2009; Bech and Monnet, 2016; Allen et al., 2020; Bianchi and Bigio, 2022). Our contribution relative to this strand is the introduction of persistent, ex-ante bank heterogeneity. Our interbank modeling and solutions approach is related to the micro origins and networks channel of monetary policy (Carvalho, 2014; Ghassibe, 2021a,b; Baqaee et al., 2023). Our quantitative and empirical emphasis on assortative matching is related to the literature on sorting and sequential search (Chade et al., 2017).

Third, we contribute to the vast literature on banks and macroeconomic effects of financial crises. Classic and some recent papers include Diamond (1984); Diamond and Dybvig (1983); Bernanke and Blinder (1988); Bernanke et al. (1999); Bernanke and Gertler (1995); Allen and Gale (1998, 2004); Brunnermeier and Sannikov (2014); Gertler et al. (2016, 2020); Nuno and Thomas (2017); Begenau et al. (2021); Bigio and Sannikov (2023); Faccini et al. (2024); Amador and Bianchi (2024). Fourth and finally, we contribute to the applied literature that studies monetary policy transmission in the euro area. Some important studies include Maddaloni and Peydro (2011); Giannone et al. (2012); Altavilla et al. (2014, 2019); Ciccarelli et al. (2013); Heider et al. (2019); Elliott et al. (2021); Bittner et al. (2023). Our contribution to this strand is to provide novel empirical evidence on the largest euro-area economy and to supplement it with a micro-founded macroeconomic framework with bank heterogeneity and endogenous liquidity management.

2 Empirical Analysis

This section discusses our data, empirical methodology, and presents the main empirical results for interbank lending patterns.

2.1 Data Description

Our dataset consists of two general parts. First, to study the interbank market we obtain bank-to-bank linked exposure data from the BAKIS-M administrative credit-registry database for Germany (Schmieder, 2006). Banks that are domiciled in Germany are required to report any exposure that exceeds €1 million.[1] The dataset contains the loan amount outstanding to the respective borrower on a quarterly basis. The sample runs from 2002 to 2019 and comprises, on average, about 1,800 banks in the role of either lender or borrower in the interbank market. We have, on average, 28,251 inter-bank connections per quarter, of which 1,740 are new links, whereas 1,451 are being terminated (see Table 1, Panel A).

[1] In January 2015 the reporting threshold was reduced from €1.5 million. Note that this reporting requirement applies to all borrowers, including those with less credit exposure, as long as the total loan amount of a given borrower's parent and all affiliated units is equal to or exceeds the threshold at any point in time during the reporting period.

Second, we use monthly balance-sheet statistics (BISTA)[2] with the coverage of banks' asset and liability positions (Gomolka et al., 2020) alongside annual income and expense information (GuV)[3] with the coverage of banks' profit and loss accounts (Stahl and Scheller, 2023). Panel B of Table 1 shows summary statistics for the main balance-sheet characteristics as of 2010.

2.2 Assortative Matching and other Facts

We start by establishing several basic stylized facts on quantities and prices that are relevant to our analysis. First, Figure 1 shows the aggregate time series for the German interbank market over 2002-2020. We note that both the total volume of transactions (intensive margin) and the number of active participants (extensive margin) have been trending down steadily over the past 20 years. This constitutes a fact that we will later replicate and match with the quantitative model.

The second stylized fact involves cross-sectional patterns in the banking and interbank market sectors. Figure 2 presents (binned) scatter plots for bank balance sheet size (proxied with (log) assets) and interbank trading volume as lender and borrower, respectively, in panels (a) and (b). In order to remove time variation, we focus on 2010:q4. In both panels, we observe an almost perfectly linear positive association in logarithms. In order for our macro-banking model to be consistent with the micro data, it is critical that the model generates the same cross-sectional pattern.

The third fact is a key empirical finding of the paper. We now turn to discussing the matching patterns in the interbank market. Figure 3 shows matrix-like graphs with size deciles of borrowers and size deciles of lenders on the horizontal and vertical axes, respectively. Size is defined as total assets. We consider the entire sample between 2002 and 2019. The intensity of lender-borrower matches is represented by the size of circles. Panel (a) weighs lender-borrower interactions by the number of matches, and Panel (b) weights lender-borrower interactions by the volume of transactions. We highlight two important observations. First, a strong, robust pattern of the data is *assortative matching by size*: large lenders match with and lend to large borrowers. This can be seen from the north-east directed concentration of both match and volume weighted matches. The reverse also holds true, i.e. large borrowers tend to match with large lenders, but there is a bit more variation in terms of the size of the lenders from which the largest borrowers source credit.

[2]Data ID: 10.12757/BBk.BISTA.99Q1-19Q4.01.01
[3]Data ID: 10.12757/BBk.GuV.9922.01.01

We document the assortative matching result more formally in a bank-counterparty-year-level panel regression, thus accounting for time-varying unobserved heterogeneity at both the lender and the borrower levels. The main independent variable is $Entity_{bt}$ which is an indicator variable for a bank b that is in the top decile of lenders (for columns 1 and 3) or borrowers (for columns 2 and 4) based on balance sheet size. The $Counterparty_{ct}$ variable refers to borrowers for columns 1 and 3 and to lenders for columns 2 and 4. The dependent variable, $Match_{bct}$, is an indicator variable that takes the value of unity in case of a relationship between a lender and a borrower in a given year y, and 0 otherwise. The dependent variable is weighted by (log) exposure volume in columns 3 and 4.

Table 2 reports the results from this panel regression. The key takeaway from this Table is that the magnitude and significance of the coefficients increase as we go down the rows. This means that conditional on being a lender in the top decile of the size distribution, an interbank market match is much more likely with a counterparty that is also in the top decile of the size distribution. This is true from the perspective of lenders (columns 1 and 3) and borrowers (columns 2 and 4), and whether matches are weighted (columns 3 and 4) or not (columns 1 and 2).

Figure 3 also speaks to another important fact: interbank market activity is almost zero in the lowest size deciles. We interpret this as evidence of *rationing out* of the smallest banks. Our model will be able to speak to this fact through the lenses of a sequential, "first-come-first-serve" matching algorithm. While the notion that banks systematically sort into borrowers of preferred profiles and furthermore build relationships is ubiquitous (Degryse and Cayseele, 2000; Chodorow-Reich, 2014; Chang et al., 2023), we document a particular form of sorting—assortative matching by size—in the context of interbank transactions for the largest euro area economy.

Finally, in Figure 4 we plot the time series of the ECB interest rate corridor—the main refinancing rate, the deposit facility rate, and the lending facility rate—along with the Euro Overnight Index Average (EONIA) rate, which is the main interbank interest rate on unsecured overnight lending in the euro area. We notice that the pass-through from movements in the refinancing rate onto the EONIA rate is almost complete. Quantitatively, the correlation between the two rates is over 99%.

2.3 Local Projections with ECB Monetary Policy Shocks

In this section, we trace out the impact of identified ECB monetary policy shocks on the intensive and extensive margins of the German interbank market. We will use these important moments for model validation in the later sections. The monetary policy shock series is depicted in Figure 5. The shocks are identified with the high-frequency approach of Jarocinski and Karadi (2020), building on Gurkaynak et al. (2005), Gertler and Karadi (2015), and Nakamura and Steinsson (2018).

Our empirical specification is a Jordà (2005)-style local projection. We first fill up our panel, including zero interbank exposure periods, for all lender-borrower pairs that have a non-zero number of transactions during our entire sample period from 2002 to 2019. We denote the interbank exposure of lender i to borrower j in quarter t by $y_{i,j,t}$, ϵ_t is the monetary policy surprise, and h the impact horizon. The baseline specification estimating the average effect of monetary policy surprises is:

$$y_{i,j,t+h} = \alpha_i + \alpha_j + \beta_h \epsilon_t + \gamma_h y_{i,j,t-1} + e_{i,j,t+h}, \tag{1}$$

where $y_{i,j,t}$ is either the natural logarithm of the exposure volume between i and j in quarter-year t (intensive margin, conditional on non-zero volume) or an indicator variable for any non-zero exposure between the two parties (extensive margin). α_i and α_j denote lender and borrower fixed effects, respectively. The coefficient of interest is β_h. To the extent that ϵ_t is exogenously assigned, $\hat{\beta}_h$ is identified. Standard errors are three-way clustered at the year-quarter, lender, and borrower-levels. Because the dependent variable may be serially correlated, we also include $y_{i,t-1}$ as an additional control.

We are also interested in understanding the heterogeneous effects of ECB monetary policy shocks. To this end, we introduce a size interaction: an indicator $s_{i,t}$ which equals one if lender i is in the top decile of the total assets distribution as of quarter t, and similarly for borrowers ($s_{j,t}$). The specification now takes on the following form:

$$y_{i,j,t+h} = \alpha_{i,t} + \alpha_{j,t} + \phi_h s_{i,t} \times s_{j,t} \times \epsilon_t + \nu_h s_{i,t} \times s_{j,t} + \gamma_h y_{i,j,t-1} + e_{i,j,t+h}, \tag{2}$$

where ϕ_h is the coefficient of interest. It captures the triple interaction between monetary policy shocks, lenders being large in size, and borrowers being large in size. Note that this specification can no longer identify the average effect due to the presence of $\alpha_{i,t}$ and $\alpha_{j,t}$. However, our interest now lies in the *relative* effects, which are identified as long as monetary policy is exogenously assigned.

Figure 6 presents the results in two stages. Panels (a) and (b) show dynamic estimates of $\hat{\beta}_h$ for $h \in [0, 8]$, varying the dependent variable to reflect either the intensive or extensive margin of interbank connections in specification (1). We document that positive (contractionary) ECB monetary policy shocks cause an expansion in the interbank market along both the intensive and extensive margin: banks establish more connections *and* lend more conditional on the existing relationships. In other words, the interbank market activity is pro-cyclical with respect to monetary policy changes.

Panels (c) and (d) of Figure 6 present dynamic estimates of $\hat{\phi}_h$ for the triple interaction term in specification (2). We find that the expansion in the intensive margin is concentrated among matches between large lenders and large borrowers. A positive and significant coefficient in Panel (c) suggests that interbank lending goes up by *more* if both lenders and borrowers belong to the top size decile. We also observe an increase in interbank lending along the extensive margin, i.e., the largest lenders expand their lending to the largest borrowers if they did not already lend to them before, but this effect materializes only over the longest estimated horizon in Panel (d).

Before proceeding to our model, we briefly summarize the empirical part of the paper. Our findings suggest that there is a strong interaction between financial intermediary balance sheet size and interbank activities: larger banks lend more and have more connections in the interbank market in general. Larger banks also tend to lend more to other large banks via the interbank market, i.e., there is evidence of assortative matching. Smaller banks, on the other hands, are more likely to get rationed out. Finally, the interbank market response to monetary policy shocks is concentrated in the matches between large lenders and large borrowers. Thus, it seems that a good general equilibrium model of banks' liquidity management should contain (i) realistic bank size heterogeneity and (ii) an active interbank market with flexible intensive and extensive margins that correlate with balance sheet size.

3 A Heterogeneous-Bank Model with Active Liquidity Management

This section presents our quantitative model with heterogeneous banks and active liquidity management. Time is infinite. There is a discrete, time-invariant number $\mathcal{N}$ of banks that are indexed by j. There is no aggregate uncertainty.

3.1 Interest Rate Corridor Policy

We start with the monetary authority which sets the interest rate corridor policy that all agents in the economy will take as given. The central bank sets the nominal refinancing rate R_t^N, the lending facility rate R_t^L, the deposit facility rate R_t^D, and the interest rate on reserves R_t^R subject to the following restriction: $R_t^L \geq R_t^N \geq R_t^D \geq R_t^R$. Following ECB practices, we maintain a rule that the net interest rate on reserves is equal to the deposit facility rate whenever $R_t^D = 1$ and zero otherwise. In the steady state, the refinancing rate is equal to the long-run target R^* which is pinned down by the rate of time preferences.

Lending and deposit facility rates are set according to a symmetric spread S_t such that:

$$R_t^L = R_t^N + S_t, \quad R_t^D = R_t^N - S_t \tag{3}$$

The spread S_t is a policy choice for the monetary authority and we will be parameterized in accordance with the German and ECB data.

3.2 Firms

There is a representative capital-producing firm. This firm is cash-strapped and requires external financing in order to operate. It obtains loans $l_{j,t}$ from the banking sector. We assume that the firm uses loans as inputs and produce units of capital $k_{j,t}$ with a one-to-one technology:

$$k_{j,t} = l_{j,t} \tag{4}$$

Competition in the loan market is perfect and units of capital get efficiently aggregated:

$$K_t = \sum_{1}^{\mathcal{N}} k_{j,t} \tag{5}$$

The law of motion of aggregate capital is standard:

$$K_{t+1} = (1 - \delta)K_t + I_t \tag{6}$$

where δ is the rate of depreciation and I_t is aggregate investment. In addition, there is a representative firm that rents labor L_t and capital K_t in order to produce a final good with a constant returns to scale production technology:

$$Y_t = K_t^{\alpha} L_t^{1-\alpha} \tag{7}$$

where $0 < \alpha < 1$. The return on aggregate capital is as follows:

$$R_{t+1}^k = \frac{A\alpha K_{t+1}^{\alpha-1} + (1 - \delta)P_{t+1}}{P_t} \tag{8}$$

where P_t is the aggregate price of capital. With perfect competition and marginal-cost pricing, P_t equates the aggregate marginal cost of banks, which is an endogenous object.

3.3 Households

Households derive utility from consuming the final good and discount the future with the discount factor β. Labor is supplied inelastically and normalized to unity. The period utility flow is as follows:

$$U(C_t, B_t) = \frac{1}{1-\phi} C_t^{1-\phi} \tag{9}$$

where ϕ is the coefficient of relative risk aversion. Households can save via bank deposits $b_{j,t}$ which pay out a state non-contingent gross return $R^B_{j,t}$. The sequence of household balance sheet constraints is:

$$C_t + \sum_1^{\mathcal{N}} b_{j,t} \leq W_t + \sum_1^{\mathcal{N}} R^B_{j,t} b_{j,t-1} + \text{Div}_t + T_t \tag{10}$$

where W_t is the competitive wage rate, $R^B_{j,t}$ is the risk-free bank-specific interest rate on deposits, Div_t are lump-sum transfers of bank dividends from exiting banks, and T_t are any remaining lump-sum transfers/taxes. In the absence of any additional frictions such as deposit market power, the interest rate on bank deposits and the risk-free rate of the economy will equalize.

3.4 Banks

The role of banks in our model is to source short-term deposits $b_{j,t}$ from households and - in combination with their own net worth $n_{j,t}$ - lend funds $l_{j,t}$ to firms that get transformed into a form of illiquid capital $k_{j,t}$. Banks are ex-ante and permanently heterogeneous in efficiency κ_j, which is a cost shifter that impacts their ability to obtain cheaper funding. Lower values of κ henceforth mean *higher* efficiency. κ is drawn by nature from a Normal distribution $\mathcal{N}(1, \sigma_\kappa)$. Banks also hold reserves s, which is a cash-like form of risk-less storage. The bank balance sheet constraint binds every period and is as follows:

$$b_{j,t} + n_{j,t} = p_{j,t} l_{j,t} + s_{j,t} \tag{11}$$

Due to moral hazard frictions as in Gertler and Kiyotaki (2010) and Gertler and Karadi (2011), banks face a capital requirement of the form:

$$p_{j,t} l_{j,t} \leq \lambda V_{j,t} \tag{12}$$

where $V_{j,t}$ is the franchise value of bank j. A minimum reserves rule is given by:

$$s_{j,t} \geq \omega b_{j,t} \tag{13}$$

where ω is a reserves requirement ratio. It is a policy choice for the monetary authority. The law of motion of net worth with *beginning-of-period* variables is:

$$n_{j,t+1} = R^K_{t+1} p_{j,t} l_{j,t} + R^R_{t+1} s_{j,t} - (1 + \kappa_j r^B_{j,t+1}) k_{j,t} - \nu_1 k^{\nu_2}_{j,t} \tag{14}$$

where the dyad $\{\nu_1, \nu_2\}$ captures non-interest rate expenses that scale with bank size, i.e. the level of bank assets. In particular, $\nu_2 > 1$ will achieve scale-variance through convexity of these expenses. Scale-variance makes bank size matter - an important ingredient of our theory. Recall that R^R is the interest rate on reserves - a policy choice for the monetary authority. Notice how a higher value of κ_j increases the net deposit rate $r^B_{j,t+1}$ at the bank level. This is a reduced-form way of capturing ex-ante heterogeneity in monitoring efficiency or skill.

To define the banks' dynamic problem we temporarily adopt recursive notation. The aggregate state vector $\mathbf{S}$ includes aggregate capital K and the price of capital P; knowing both is sufficient to pin down the return on capital, an aggregate sufficient statistic to determine bank-level choices. The idiosyncratic state vector $\mathbf{s}$ includes the permanent efficiency type κ and net worth state n. Recall that individual net worth is a state variable due to scale variance. Also recall that the deposit interest rate distribution is not a state because of the absence of the deposit spreads and equalization of the retail deposit rates with the risk-free rate. Following the literature, banks cannot operate with negative net worth and exit with an exogenous probability $1-\sigma$, which also captures a dividend payout rule. The banks' dynamic problem takes on the following form:

$$\max_{\{k,b\}} V(\mathbf{s};\mathbf{S}) = \mathbb{E}_{\mathbf{s},\mathbf{S}}\{\beta\,[(1-\sigma)n' + \sigma V'(\mathbf{s'};\mathbf{S'})]\} \tag{15}$$

subject to:

$$\begin{aligned}
&n' = R^{K'}(\mathbf{s'};\mathbf{S'})pl + R^R s - (1+\kappa r^B)b - \nu_1 k^{\nu_2} \\
&b + n = s + pl \\
&pl \leq \lambda V(\mathbf{s};\mathbf{S}) \\
&s \geq \omega b
\end{aligned}$$

One can show that the marginal cost is:

$$MC = \frac{\nu_1 \nu_2 l^{\nu_2 - 1}}{\mathbb{E}_{\mathbf{s},\mathbf{S}} R^{K'}(\mathbf{s}';\mathbf{S}') - \frac{1+\kappa r^B - R^R \omega}{1-\omega} - \gamma(\mathbf{s};\mathbf{S})\lambda} \tag{16}$$

where $\gamma(\mathbf{s};\mathbf{S})$ is the Lagrange multiplier on the leverage constraint. Due to perfect credit market competition, the price of loans equates the marginal cost, thus $p = MC$. As a result, loan prices are pinned down by the marginal cost, deposit rates are determined by the risk-free rate, and quantities $\{k, b\}$ are obtained from 15.

3.5 Uninsured Idiosyncratic Deposit Withdrawal Risk

Financial markets are incomplete and banks face uninsured idiosyncratic deposit withdrawal risk $\xi_{j,t}$. Suppose that households are subject to preference shocks as in Diamond and Dybvig (1983) which require them to suddenly become impatient and withdraw deposits from bank j in order to either deposit the same amount at another bank k or save it in a different financial vehicle. $\xi_{j,t}$ is drawn from a mean-zero distribution with variance σ_ξ^2.

Unexpected fluctuations in $\xi_{j,t}$ generate a precautionary savings motive for banks. Their precautionary buffer stock of wealth is in the form of reserves $s_{j,t}$. A negative realization of $\xi_{j,t}$ creates a deficit in reserve holdings. On the other hand, a positive realization creates excess reserves which the bank may want to invest into productive activities for a higher-than-risk-free rate of return.

The surplus/deficit in reserves is denoted by $\Delta_{j,t}$ and can be defined as follows:

$$\Delta_{j,t} \equiv \omega b_{j,t} + \frac{\left(1 + \kappa_j r^B_{j,t+1}\right)}{R^R_{t+1}} \xi_{j,t} b_{j,t} - \omega b_{j,t}\left(1 + \xi_{j,t}\right) \tag{17}$$

The first two terms in Equation 17 summarize the reserve balance and the third term the required reserves level after the shock $\xi_{j,t}$, respectively. Following Bianchi and Bigio (2022), we adopt the convention that the bank pays interest on deposits no matter if they get withdrawn, and thus any transfer is settled with $\frac{\left(1+\kappa_j r^B_{j,t+1}\right)}{R^R_{t+1}}$ reserves. It's clear that in the absence of $\xi_{j,t}$ shocks, there are no surpluses or deficits.

3.6 Interbank Market

After deposit withdrawal shocks $\xi_{j,t}$ are realized, banks must settle their reserve shortages by the end of the period. To this end, we allow for an over-the-counter settlement market, which is similar to Afonso and Lagos (2015) and Bianchi and Bigio (2022) with one crucial difference: because banks are ex-ante heterogeneous in our model, clearing the interbank market requires additional assumptions.

We propose an iterative algorithm for discrete-number heterogeneous-agent setups in the spirit of Atkeson and Burstein (2008). The interbank market is settled in rounds. All potential lenders - banks with realizations of $\xi_{j,t} > 0$ - and potential borrowers - banks with realizations of $\xi_{j,t} < 0$ - are ranked in descending order according to their efficiency indicator κ_j. In equilibrium, κ_j heterogeneity in combination with scale-variance leads to a monotonic positive correlation between beginning-of-period net worth $n_{j,t}$ and (the inverse of) κ_j. Thus, the largest and most efficient banks will get to "choose" first. An important degree of freedom in our algorithm is whether the market is borrower- or lender- driven, i.e. who gets to solve the portfolio problem. We assume that it is *borrowers* who approach lenders in an iterative manner.

Denote with x^L and x^B the integer ranks of lenders and borrowers, respectively. For example 1^B denotes the first-ranked borrower: this bank is the most efficient and therefore gets to solve its portfolio problem first. Each borrower minimizes borrowing costs subject to two types of costs that are associated with establishing a single incoming connection. First, if the borrower borrows from another bank then it must incur convex variable costs that are parametrized by the pair $\{\varphi_1, \varphi_2\}$. These costs are *match-specific* and scale not only with the volume of the transaction but also the ranks x^L and x^B. The total variable cost for a transaction of volume q between borrower B and lender L is as follows:

$$VC_{BL} = x^L \times x^B \times \varphi_1 q^{\varphi_2} \tag{18}$$

As a result, variable costs will be low if high-ranked borrowers and lenders are matched together. This friction will deliver an active intensive margin and positive assortative matching in equilibrium. Parameters $\{\varphi_1, \varphi_2\}$ will be made empirically consistent with our German data in the following section. The second cost of an interbank connection is a minimum volume cutoff $\underline{q}$ which applies to every individual transaction. In other words, if a bank borrows from five different borrowers, it must ensure that each borrowing amount is above $\underline{q}$ five separate times. The cutoff parameter is used to establish a region of inaction (extensive margin) in the market.

The interbank interest rate is denoted as R_t^I and is subject to the following restriction: $R_t^L \geq R_t^I \geq R_t^D$. Throughout the rest of the paper, we will assume that while banks take R_t^I as given, in equilibrium the monetary authority always ensures that $R_t^N = R_t^I$ holds, a condition that is true for the majority of our empirical sample.[4]

The interbank market is cleared sequentially in the following manner:

Interbank Market Clearing Algorithm

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1. Round 1 starts. First-ranked borrower 1^B must cover its reserves deficit Δ_{1^B} conditional on the prevailing cost structure and the interest rate corridor. The borrower compares two options. First, it can borrow from a first-ranked lender 1^L subject to the interbank market rate R_t^I and the associated fixed and variable costs. Second, it can borrow from the lender of last resort at R_t^L subject to a possible penalty rate (the spread between R_t^L and R_t^I). The borrower chooses the quantity q of how much to borrow from 1^L by minimizing the total cost of borrowing subject to the outside option:

$$TC = q \times \left(R_t^I - R_t^L\right) + 1 \times 1 \times \varphi_1 q^{\varphi_2} \tag{19}$$

The desired quantity q^* must satisfy the capacity constraints: $q^* = \min\left[\min\left(|\Delta_{1^L}|, |\Delta_{1^B}|\right), q^*\right]$. That is, the desired volume cannot surpass the absolute value of either the deficit of the borrower or the surplus of the lender. Finally, q^* must be above the cutoff $\underline{q}$.

2. Iterate over all lenders. If the borrower satisfies its total demand such that $\Delta_{1^B} = 0$ before it reaches the final lender, the round breaks and the next borrower in line resumes.

3. Iterate over all borrowers.

4. If a lender x has any surplus remaining, it invests Δ_{x^L} into the deposit facility at the rate R_t^D.

5. If a borrower x has any deficits to cover, it borrows the amount Δ_{x^B} from the central bank at the lending facility rate R_t^L.

6. Market closes.

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[4]Recall that the correlation between changes in the refinancing rate and changes in the EONIA rate is 99%.

Graphical Illustration A rich spectrum of outcomes is possible in our interbank market. First, a borrower is free to set $q^* = 0$ right from the start, in which case it borrows solely from the lender of last resort. This occurs if the cost structure and/or the interest rate spread are too prohibitive. Second, it may decide to borrow some positive amount q^* from the first lender. That amount, in turn, may or may not be constrained by the lender's available reserves surplus. If q^* is greater than Δ_{x^L}, then the borrower's demand is not completely satisfied as it will be forced to go down the pecking order of lenders and explore less efficient matches. Third, the borrower may be "rationed out" from the market if all of the possible matches have already been formed before its turn. In this case, the borrower is forced to borrow from the central bank. Finally, the borrower's ideal choice q^* might fall below the cutoff $\underline{q}$ constraint, i.e. the region of inaction.

To illustrate the above mechanisms further, we show the first round of the clearing algorithm visually. Figure 7 plots on the horizontal axis the grid of possible amounts q that the first-ranked borrower 1^B can choose to borrow from 1^L. On the vertical axis are the associated values of excess total costs TC, conditional on the outside option. As q goes up, TC falls and then rises. The interior solution is exactly q^*, i.e. the ideal amount that the borrower wishes to borrow from 1^L. However, this amount is greater than both Δ_L and $|\Delta_B|$. Thus, the final volume that gets traded is $q^* = |\Delta_B|$. The cutoff $\bar{q}$ is satisfied as it is a small number. In this situation, the borrower's full demand is satisfied, the round breaks, and the second-ranked borrower 2^B resumes. We keep track of the fact that the first lender's remaining surplus is now much lower as it had just traded with 1^B. Thus, the second-ranked borrower 2^B may have to trade an inefficiently lower amount with 1^L because it must enter the interbank market second. Thus, 2^B is more likely to trade more with 2^L, a match that would be more expensive due to rising match-specific variable costs. A match is therefore less likely, increasing the chance that 2^B borrows from the central bank at a higher rate. This domino effect continues until all borrowers get to choose or all lenders' surpluses get traded and some low-ranked borrowers are rationed out.

End-of-period Net Worth We can now characterize end-of-period bank net worth *after* the closure of the interbank market. Denote by $A^B_{j,t}$ and $B^B_{j,t}$ bank j's borrowing from the interbank market and the deposit facility, respectively. Thus:

$$\hat{n}^B_{j,t+1} = n^B_{j,t+1} - \left(R^I_t - 1\right) A^B_{j,t} - \left(R^L_t - 1\right) B^B_{j,t} \tag{20}$$

And similarly for the lenders:

$$\hat{n}^L_{j,t+1} = n^L_{j,t+1} + \left(R^I_t - 1\right) A^L_{j,t} + \left(R^D_t - 1\right) B^L_{j,t} \tag{21}$$

where with $\hat{x}$ we denote *end-of-period* variables, i.e. after the interbank market closes. Economy-wide aggregate net worth is therefore:

$$\hat{N}_t = \sum_{j \in L} \hat{n}^L_{j,t} + \sum_{j \in B} \hat{n}^B_{j,t} \tag{22}$$

Absent idiosyncratic deposit withdrawal shocks, N_t and $\hat{N}_t$ equalize.

3.7 Equilibrium

A *stationary competitive equilibrium* (SCE) is characterized by a vector of exogenous aggregate prices $\{R^R, R^D, R^N, R^L\}$, endogenous aggregate prices $\{P, R^K\}$, endogenous aggregate quantities $\{K, N, B, \hat{N}, Y, C\}$, bank-level policies $\{l_j, b_j, n_j, p_j, s_j, R^B_j, \hat{n}_j\}$, and the bank-level value function V_j, such that:

1. bank policies and the value function solve the banks' optimization problem;
2. the household and non-financial firms optimize according to their problems;
3. aggregates are consistent with the respective cross-sectional distributions: $K = \sum k_j$, $N = \sum n_j$, $K = \sum B = b_j$, $\hat{N} = \sum \hat{n}_j$, $P = \frac{\sum p_j}{N}$, $R^B = \frac{\sum R^B_j}{N}$, $S = \sum s_j$;
4. markets for retail deposits, interbank transactions, and loans clear;
5. goods market clears: $Y = C$;

We solve our model numerically using standard projection methods. Following Faccini et al. (2024) we will assume that the leverage constraint is always binding, as well as the reserves requirement constraint. Finally, we assume that all non-interest expenses are rebated back to the household in the form of lump-sum payments and get consumed.

4 Model Quantification and Validation

In this section we begin to bring our model to the data. First, we parameterize the model by targeting select moments from the German data. Second, we study steady-state properties and parameter statics. Third and finally, we validate the model by showing that it predicts key cross-sectional and sorting relationships that are in line with the data.

4.1 Calibration

Table 3 reports ours model parameterization strategy along with the sources and targets per each parameter. We discuss our calibration approach block by block, beginning with the basic macro parameters. Concavity of the production function α is set to 0.36. The discount factor β is set to 0.995 in order to target a refinancing rate of 2% p.a. which corresponds to the historical average over 2003-2023 in our data. We set the risk aversion parameter $\psi = 1$ and assume full capital depreciation ($\delta = 1$).

Moving on to the interbank market, we calibrate $\underline{q}$ to match the empirically observed region of inaction (RoI). We define RoI as the ratio of the number of active interbank links over the total number of possible links. RoI is theoretically bounded by zero and unity and we target a RoI of 5% in the model. In the data, it is in the rough region of between 1% and 10%.

Parameter ψ_1, which governs the linear component of the variable interbank match cost, is a key parameter in the model. This parameter controls the relationship between bank size and interbank trading intensity. Using our data, we run a linear regression with (log) interbank borrowing as the dependent and (log) bank assets as the independent variable. We also include a time fixed effect. The resulting elasticity is 0.55. We then calibrate ψ_1 in order to achieve the same elasticity in the model. We normalize ψ_2, i.e. the power component of the match cost function, to 2.

There are several parameter choices that must be made for the bank balance sheet block. Volatility of permanent heterogeneity in efficiency - σ_κ - is set to 4.2% which corresponds to the cross-sectional standard deviation of profits over assets, as seen from Table 1, and captures variability in profitability. The exogenous survival probability σ is set to 0.973 (per quarter) following Gertler and Kiyotaki (2010), which implies that banks live on average for around 9.25 years.

The pair of parameters $\{\nu_1, \nu 2\}$ is another important parameters in the model as they determine convex non-interest expenditures and, as a result, the departure from scale invariance. We normalize ν_2 to 2. To calibrate ν_1 we compute the average ratio of non-interest expenses to assets in the German data. We define assets as total loans to non-banking institutions since this is the correct object in the model. The ratio was 1.9% as of 2010:q4 (in "normal times"). Volatility of the stochastic deposit withdrawal process σ_ξ is important for determining the strength of the precautionary motive and the aggregate demand for interbank-market services. We reverse engineer σ_ξ such that the interbank market loans to assets ratio hits our empirical target of roughly 13%, a number that also corresponds to 2010:q4. The final component of the bank balance sheets block is λ, a parameter that determines the fraction of divertible assets and thus the moral hazard friction in the banking sector. We calibrate λ so that the average leverage ratio in the model is equal to 11, which corresponds to average leverage over the entire sample (average leverage as of 2010:q4 was 11.65). As with non-interest expense ratios, we define leverage as lending to non-banks over capital.

The final remaining block that we must parameterize involves policy choices. The reserve requirement ratio ω is set to 1.65%. The interest rate on reserves is set at 1.287% per year. Finally, the symmetric interest rate spread S is equal to 1.23% per year. All three values correspond to ECB averages across our sample. Finally, we assume that the number of banks in our economy is $\mathcal{N} = 100$.

4.2 Steady States and Special Cases

We begin the quantitative inspection of our model with the analysis of the SCE. Recall that this corresponds to the stationary equilibrium where all aggregate quantities are time-invariant. Table 4 reports key financial and macroeconomic aggregates in the baseline economy and in four illustrative special cases.

In column (1) of Table 4 we present the baseline economy. We first report the total interbank (IB) market volume and the IB volume that is attributed to the 10% largest banks (size in terms of total assets). We see that the 10% largest banks are responsible for almost 70% of all IB market activity. Next, we report two extensive margin metrics. The first one is the fraction of active matches, defined as the number of active matches over the total number of possible matches. A low value of 5% suggests that the IB market is highly concentrated and the extensive margin is very active. The second metric is the ratio of active borrowers over total borrowers. The value of 0.47 indicates that 47% of borrowers get to trade in the interbank market and the remaining 53% are either rationed out or find the market too cost-prohibitive. Again, this suggests a very active extensive margin.

The next five rows report key bank balance sheet characteristics: average total assets, net worth, deposits, market leverage, and the price of capital. Finally, the last two rows correspond to aggregate production and aggregate consumption. Notice that consumption is defined as inclusive of non-interest expense receipts, as mentioned previously.

We now study column (2) of Table 4, which presents an important special case of our model with no interbank match costs, i.e. when ν_1 is set to zero. Comparing this economy with the baseline identifies the impact of interbank market frictions on steady-state outcomes. We make three general observations. First, relative to the frictionless counterfactual (column (2)), the baseline economy (column (1)) features a much shallower interbank market in terms of both intensive and extensive margins. Total volume is 80% smaller and the fraction of active borrowers is almost halved from 0.88 to 0.47.

Second, the financial sector is smaller and *riskier*. The baseline economy features banks with less total assets, net worth, and deposits. In addition, the average leverage ratio is higher. The frictional interbank-market baseline prevents financial intermediaries from managing uninsured deposit withdrawal risk. Because the marginal cost of transactions is high, fewer banks participate in the interbank market, more banks borrow from the lender of last resort and at a penalty rate, and more banks park excess reserves in the less-remunerated deposits facility. As a result, the economy is more fragile as aggregate bank net worth is down around 5%. Third and finally, both aggregate output and consumption are down - by 40 and 76 basis points in relative terms, respectively. The more fragile banking sector lends less to the non-financial firm, who in turn produces less productive capital, yielding a lower quantity of the final good. Since households also get compensated for non-interest expenditures, aggregate consumption takes an additional hit. All in all, we conclude that interbank-market frictions are inefficient and lead to considerable output and consumption losses in the steady state.

Column (3) of Table 4 reports results from a special case of our model with no minimum quantity cutoffs $\underline{q}$. We see a substantial increase in interbank-market activities as total volume almost doubles. Because $\underline{q}$ primarily controls the extensive margin, we see a dramatic increase in the two extensive-margin variables. In particular, 100% of all borrowers participate in the market at least once. A more efficient interbank market translates into a larger banking sector that is also less fragile. Finally, aggregate production and consumption are up - for the similar reasons as before. Quantitatively, we notice that the macroeconomic impact of removing quantity cutoffs $\underline{q}$, which heuristically represent a form of "fixed costs", is smaller than in the case of the removal of match costs.

Column (4) of Table 4 showcases the last scenario where we dramatically reduce the volatility of stochastic deposit withdrawal shocks σ_ξ and set it to a small number. Absence of idiosyncratic shocks to deposits removes the need for the interbank market as the volume shrinks to zero, as does the number of active participants. In the absence of idiosyncratic shocks, the banking sector is characterized by more assets but less net worth. This is due to the abolishment of the precautionary saving motive which was pushing up net worth in the baseline economy. The low-volatility economy is fundamentally less but endogenously more risky, which resembles the volatility paradox (Brunnermeier and Sannikov, 2014).

4.3 Stationary Distributions

We continue the presentation of quantitative results by showcasing select stationary distributions of the banking sector and the interbank market. Figure 8 plots the densities of bank assets k_j and deposits d_j in the upper two panels. Recall that in the standard model such distributions do not exist due to scale invariance and linearity of the banking problem with respect to size. In our framework, however, the distribution of bank size is a key equilibrium object for the following reason. Ex-ante heterogeneity in κ_j gives rise to ex-ante differences in the cost of funds and thus the marginal cost of running a banking franchise. For a given level of the net worth state n_j, banks with different types of κ_j will choose varying quantities of assets, deposits, and reserves. This cross section is critical for the interbank market because our sequential clearing mechanism relies on a well-defined ranking system, which in our case is determined by pecking order of efficiency (the inverse of κ_j). In addition to the above, the two lower panels of Figure 8 plot stationary distributions of interbank lending and borrowing. These correspond to objects A_j^B and A_j^L, respectively, from Section 3.6. These smooth densities are right-skewed, implying that a small fraction of intermediaries engages in a large amount of trading.

4.4 Cross-Sectional Relationships

In this section we present the model counter-part of a key empirical relationship from Figure 2: there is a strong positive correlation between bank balance sheet size and both interbank lending and borrowing volumes. In Figure 9 we present the same objects based on the stationary equilibrium of our model. There is a clear positive association between bank size and the volume of both lending and borrowing. Here, we proxy size with bank net worth but the exact same relationships hold if we replace the horizontal axes with assets or deposits. This observation reveals the following. Conditional on receiving a positive deposit shocks ξ_j, lenders that have more beginning-of-period net worth engage in more intense interbank trading. Similarly for the borrowers - banks that draw a negative deposit withdrawal shock - who borrow more from other banks in the interbank market if they are large.

The unifying object that relates balance sheet size and interbank trading intensity is ex-ante heterogeneity in efficiency κ_j. First, bank size emerges in equilibrium because of κ_j. Second, κ_j indirectly (by affecting beginning-of-period net worth) affects the ranking order in the interbank market for both lenders and borrowers. As a result, the empirically-validated positive relationship between bank size and interbank trading arises naturally. The ability of our model to match the empirical moment of Figure 2 constitutes an important validation test of our mechanism.

4.5 Assortative Matching in the Interbank Market

A key empirical finding of our paper is the presence of assortative matching in the German interbank market: large banks lend to and borrow from other large banks. This empirical regularity was documented in Figure 3. We now construct a matrix-like figure that closely resemble the empirical counterpart. Figure 13 plots borrowers (ranked by net worth n_j) and lenders (also ranked by n_j) on the horizontal and vertical axes, respectively. Panel (a) shows bank-to-bank interbank (log) lending volumes, which represents the intensive margin in the market. Panel (b) instead plots binary indicators with unity standing for an existing connection, which gauges the extensive margin.

Two important observations are noteworthy from this graph. First, the model generates equilibrium *assortative matching* by size. The north-east sloped pattern of matching shows that large lenders establish connections with and lend to large borrowers. This is an essential ingredient of our theory, which is strongly present in the German administrative data as shown previously. Second, the extensive margin is very active in our model. Smaller borrowers and lenders do not engage in any interbank trading at all, as evidenced by a large mass of zeros in the bottom panel of the Figure. This suggests that a non-trivial number of banks are *rationed out*, either due to prohibitively high marginal (φ_1) or fixed ($\underline{q}$) transaction costs. Those borrowers are forced to borrow from the lender of last resort at a penalty rate, which feeds into a lower level of end-of-period net worth. At the same time, lenders are forced to park excess reserves at the deposits facility and earn a lower return. Thus, both borrowers and lenders would prefer to trade more in the interbank market and gains from trade are possible but prevented by the cost frictions.

Overall, the banking sector and the interbank market in our model are consistent with the data along several dimensions. First, we are able to generate realistic-looking stationary distributions of bank size and interbank trading. Second, there is an empirically consistent positive correlation between bank balance sheet size and both interbank lending and borrowing. Third and finally, there is assortative matching in the interbank market based on balance sheet size.

5 Quantitative Analysis

Having validated our framework, we now proceed with several quantitative exercises. We will start by using our model to match the secular decline in aggregate interbank trading over. Then, we model impulse responses to monetary and liquidity policies. Finally, we extend the basic model with imperfect competition in the deposit market.

5.1 The Secular Decline of Interbank Lending: Model Meets Data

The basic stylized fact of the German interbank market - as showcased in Figure 1 - is two-fold. First, the *volume* of transactions has declined steadily over the past 20 years. Second, the *number* of active participants has also declined, although there is a notable counter-cyclical aspect to this trend.[5] We now use our quantitative framework and generate the same time-series trend. There are three main ingredients in this exercise. First, the parameter $\varphi_{1,t}$ is now time-varying. We will reverse-engineer the path of $\varphi_{1,t}$ that is necessary to generate the targeted decline in aggregate trading volume. Second, the *targeted* moment is the period-by-period total aggregate interbank lending $\int A^L_{j,t}$ (or, equivalently, total interbank borrowing $\int A^B_{j,t}$). In other words, we compute the path of $\varphi_{1,t}$ necessary to match the decline in $\int A^L_{j,t}$ that matches the data exactly. We also compute an object that captures the extensive margin and is calculated as a fraction of borrowers that are active in the market, as defined previously. This moment is untargeted. For simplicity, we will be estimating a *linear* trend and trying to match the change as of 2019 relative to 2002.

Figure 11 plots the result of this exercise. In the lower panel, we plot the calibrated path of $\varphi_{1,t}$ that the model says is necessary to generate the empirically observed reduction in interbank trading volumes. This decline is shown on the upper panel in two variations. First, we plot the model-implied fall in trading volumes, which is a targeted moment and matches the data exactly. Second, we show the model-produced decline in the extensive margin, which is an untargeted moment. Thus, the model correctly predicts that structural declines in intensive and extensive margins of the market are synchronized.

It's important to highlight that the implied assumption behind this exercise is that the decline in interbank trading in Germany was due to rising frictions and the interbank market becoming more costly. This is precisely the logic behind the rising $\varphi_{1,t}$ in our simulation. An alternative, observationally equivalent, approach is to suggest that the deposit facility has become cheaper and therefore more attractive for borrowers - everything else equal - than the interbank market. While we are not able to *identify* the root cause of structural changes in the interbank market, our goal is to show that our model can speak on these important issues. Future research could improve identification by, for example, combining our model with more administrative micro data.

[5] The demand for interbank borrowing goes up in recessions in response to greater liquidity risk.

5.2 Impulse Response to Monetary and Liquidity Policy Shocks

5.2.1 Monetary Policy

In this section we conduct three conditional tests in the model. Our numerical approach closely follows Boppart et al. (2018) and computes model transition dynamics following unexpected "MIT" shocks. We begin by studying the effects of unexpected changes in the non-systematic component of monetary policy. We consider a one-time mean-reverting exogenous shock to two objects. First, a positive shock to R_t^N that amounts to 2.4% p.a. Second, a positive shock to the symmetric spread S_t that amounts 1.5% p.a. This corresponds to the different shapes of the ECB interest rate corridor over the past years: the high-interest high-spread environment of 2000-2009 and the low-interest low-spread environment of 2010-2019. Thus, our experiment amounts to studying the effects of a simultaneous hike of the main policy rate and widening of the interest rate corridor.

Figure 12 presents the impulse response functions. The monetary shock hits at quarter 3, before which the economy is at the steady state. Following the shock, the interest rate and the spread revert back with the autocorrelation rate of 0.5. The economy reacts on impact, because the shock was not pre-announced before and comes as a complete surprise, and reverts back to the steady state slowly.

We now discuss several observations. First, bank assets and net worth shrink and the economy contracts as aggregate output falls. This is driven by the perfect pass-through from R_t^N to the retail deposit rate R_t^B, which raises the banks' cost of funds, leading to deleveraging, a fall in lending, and a decline in production of capital and final goods. The marginal cost goes down as the demand for intermediation is low. As a result, because of perfect credit market pass-through, the price of capital also falls. Second, total lending and the number of connections - i.e. both the intensive and extensive margins - in the interbank market *go up*. Moreover, the total response is driven by the large banks (defined as those in the top 10% of the net worth distribution) whose trade volume increases significantly. This corresponds to the positive and significant sign of the heterogeneous effect of the intensive margin in our local projections exercise (Figure 6).

The rise of interbank market activities following monetary contractions is in line with our empirical analysis and is due to the following effect. Recall that a higher refinancing rate R_t^N is accompanied by a wider interest rate corridor. A higher spread pushes up the lending facility rate R_t^L and brings down the deposit facility rate R_t^D subject to the interest rate on reserves constraint. From the perspective of borrowers, i.e. banks that draw negative deposit withdrawal shocks, this ceteris paribus makes the interbank borrowing option more attractive. This can be seen clearly from Equation 19. A higher spread increases the cost of the outside option, pushing down the relative total cost of the interbank option. Thus, the volume of trade and the action region both go up. All in all, model impulse responses are consistent with the empirical evidence from local projections.

5.2.2 Reserve Requirements

We not consider exogenous, transitory changes in liquidity policies. Our instrument of interest is the reserve requirement ratio ω_t, which is now time-varying. We assume that before the shock occurs, the economy is in the steady state with $\omega_t = 0$, i.e. there is no requirement to hold any reserves. Then, ω_t increases unexpectedly to 1.62% - the baseline value - but reverts back to the no-reserves steady state with the autocorrelation coefficient of 0.5.

Figure 13 presents the results. We see that a transitory increase in reserve requirements is generally contractionary. Recall that we assume that the liquidity constraint is always binding. A higher ω_t crowds out funding to the non-financial firm. Instead of providing more loans, the bank holds more liquidity as safe storage. As a result, aggregate lending and total output both fall. As the demand for intermediation has fallen, the price of capital also goes down in tandem with the marginal cost. In the meantime, everything else equal, a higher ω_t dampens the distortive effects of idiosyncratic deposit withdrawal shocks ξ_j. The banking sector has a larger buffer stock of liquidity and can withstand the same idiosyncratic fluctuations more resiliently. As a result, the volume of trade and the region of action in the interbank market go down for the same level of the interest rate corridor. Finally, note that the level of net worth goes up even though assets fall. This implies that the leverage ratio falls - the financial sector is less fragile. Higher reserves requirements, i.e. tighter liquidity policies, achieve greater resiliency but at the cost of less lending and production.[6]

5.3 Introducing Deposit Market Power

A salient feature of the banking data is the presence of a deposit spread between the retail deposit rate and the policy rate of the central bank. An important series of contributions by Drechsler et al. (2017) and Drechsler et al. (2021) has put forth the so-called deposits channel of monetary policy transmission which relies on bank market power in the deposits market. Quantitative studies such as Jamilov and Monacelli (2023) have since introduced deposit market power and heterogeneous deposit mark-downs into

[6] To complement the analysis of transitory liquidity policies, we have also considered shocks to the interest rate on reserves R^R. However, those have turned out to be quantitatively mild and are thus omitted for brevity.

macro-banking frameworks and found that the deposits channel impacts business cycle fluctuations.

In the case of our German data, the spread between deposit rates and the refinancing rate is very stark. Figure 14 plots the policy rate corridor together with the household deposit rate (which is the measure that corresponds correctly to our model). Notice how the spread is large on average and is generally procylical - banks actively trade off the benefit of a larger spread during times of monetary contractions versus the cost of a deposit withdrawal and an ensuing lending decline. The pass-through from changes in the policy rate to deposit rates is low. Note a particularly low pass-through episode during the 2022-2023 contractionary phase.

In order to generate an equilibrium deposit spread, we now augment our model slightly. First, we assume that households derive utility from deposit holdings because they provide special liquidity services. The period utility function now takes on the following form:

$$U(C_t, B_t) = \frac{1}{1-\phi} C_t^{1-\phi} + \chi B_t \tag{23}$$

where χ determines the extent of deposit market power of banks. This power is rooted in preferences: households desire deposits for their liquidity services and banks, fully internalizing this, pay a lower interest rate. We assume that deposit franchises are perfect substitutes:

$$B_t = \sum_{j}^{\mathcal{N}} b_{j,t} \tag{24}$$

The deposit rate is now priced according to a Lerner-type equation that sets a *mark-down* over the risk-free rate:

$$R^B_{j,t+1} = \left(1 - \frac{U_B(C_t, B_t)}{U_C(C_t, B_t)}\right) R_{t+1} \tag{25}$$

The object in brackets corresponds to the *mark-down*, which is positive whenever $\chi > 0$. The household budget constraint is now:

$$C_t + \sum_{1}^{\mathcal{N}} b_{j,t} + M_t \leq R_t M_{t-1} + W_t + \sum_{1}^{\mathcal{N}} R^B_{j,t} b_{j,t-1} + \text{Div}_t + T_t \tag{26}$$

where M_t are mutual fund holdings and R_t is the real risk-free interest rate on those holdings. For as long as $\nu_1 > 0$, positive marginal utility from deposit holdings leads to deposit market power of banks and a positive spread term $\frac{U_B(C_t,B_t)}{U_C(C_t,B_t)}$ which yields a mark-down over the risk-free rate. We are interested in tracing out the quantitative impact of deposit market power on the interbank market channel. We calibrate χ in order to hit the deposit spread of roughly 0.6% in the imperfect-competition steady state.

Our main experiment involves fitting the exact time series of the ECB interest rate corridor into our model and computing the implied macroeconomic and financial aggregates conditional on the perfect- (PC) and imperfect-competition (IC) assumptions. The inputs into the model are reported in 14 - these are the aforementioned lending facility, deposit facility, and refinancing interest rates over 2003-2023.

Figure 15 reports the results from this simulation. We highlight three interesting observations. First, the retail deposit rate is much lower on average in the IC counterfactual. This is intuitive and driven by the homogeneous deposit mark-down. Second, financial aggregates (assets and deposits) are greater on average. This standard outcome is the result of our monopolistic competition assumption: banks pay a lower interest rate to depositors, which reduces cost of liabilities everything else equal, leading to more lending and production for the same level of net worth. Third, the extensive margin of the interbank market (bottom right plot) is considerably affected by the IC assumption. When banks have market power, the region of action in the interbank market is a lot higher. Recall that the extensive margin is primarily controlled by the minimal transaction cutoff $\underline{q}$. Larger banks borrow and lend in greater amounts, reducing the probability that the $\underline{q}$ will bind. Finally, while the *level* of interbank trading volumes is higher in the IC economy, the ratio over total assets is quantitatively unchanged. This ratio is driven by other model fundamentals such as the magnitude of idiosyncratic deposit withdrawal risk.

To conclude, we find that deposit market power significantly interacts with the interbank market and the financial sector: it expands the extensive margin of interbank lending, increases aggregate lending and production, but results in lower interest rates on household deposits, thus leading to ambiguous implications for welfare.

6 Conclusion

This paper has presented a tractable, general equilibrium framework for monetary and liquidity policy analysis with bank heterogeneity and active liquidity management. We supplement our quantitave theory with detailed empirical work that leverages administrative bank-to-bank linked data from Germany. The interbank market is at the center stage of our analysis. In equilibrium, the interbank market in the model features *assortative matching* among the largest banks and *rationing out* of the smallest banks. This prediction is strongly validated in the data. The interplay between the frictional interbank market and ex-ante bank heterogeneity generates non-trivial macroeconomic implications. In particular, we find that assortative matching is inefficient: it leads to less interbank-market activity, a smaller and riskier banking sector, and lower aggregate production. Furthermore, contractionary monetary policy in the model expands interbank trading volumes and action regions all the while tightening the real economy. This conditional pattern is also supported by the data. Overall, our micro-consistent macro-banking framework offers a laboratory for policy-relevant analysis of structural counterfactuals. Future studies can expand on our work by focusing on non-conventional monetary policy in the model and in the data.

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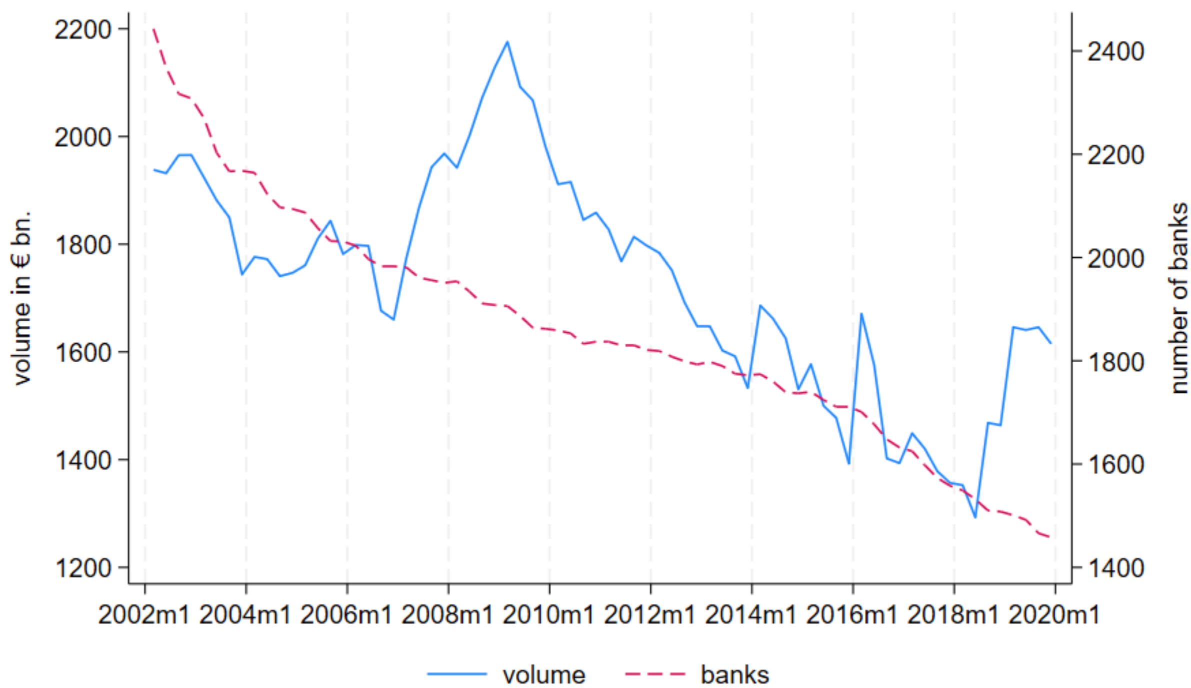
Figures

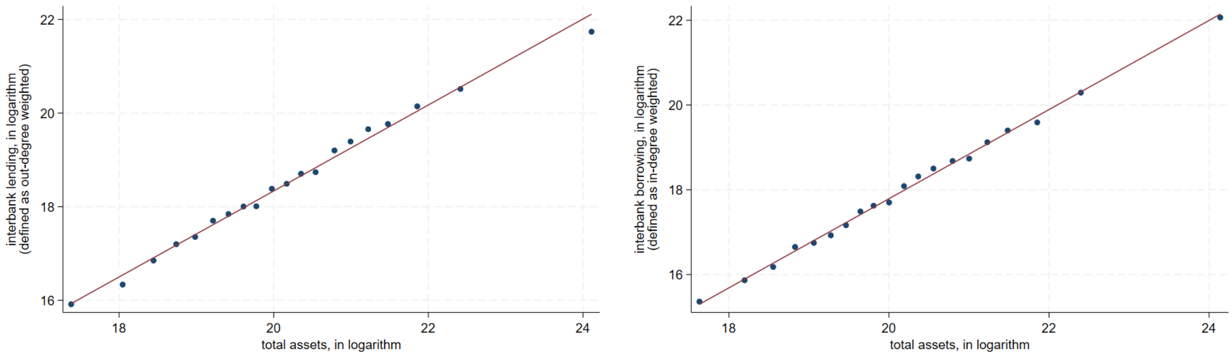
Figure 1: German Interbank Market over Time



Notes: Time series of the total volume of transactions in the interbank market (straight line) and the number of active participants in the interbank market (dashed line) in Germany.

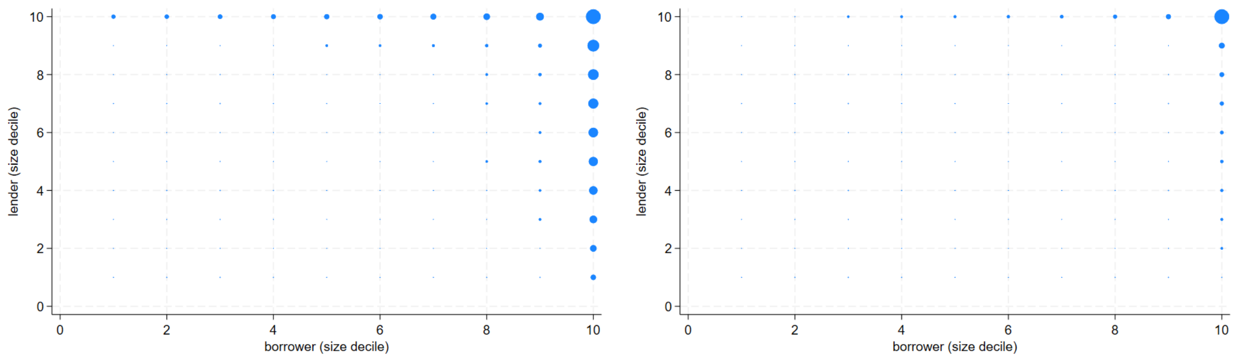
Figure 2: Stylized Cross-Sectional Facts

(a) Bank Size and Interbank Lending **(b)** Bank Size and Interbank Borrowing



Notes: Binned scatterplots of (log) total bank assets on the horizontal axis and interbank (log) lending and (log) borrowing on the vertical axes of panels (a) and (b), respectively. The data is from 2010:q4.

Figure 3: Assortative Matching in the German Interbank Market

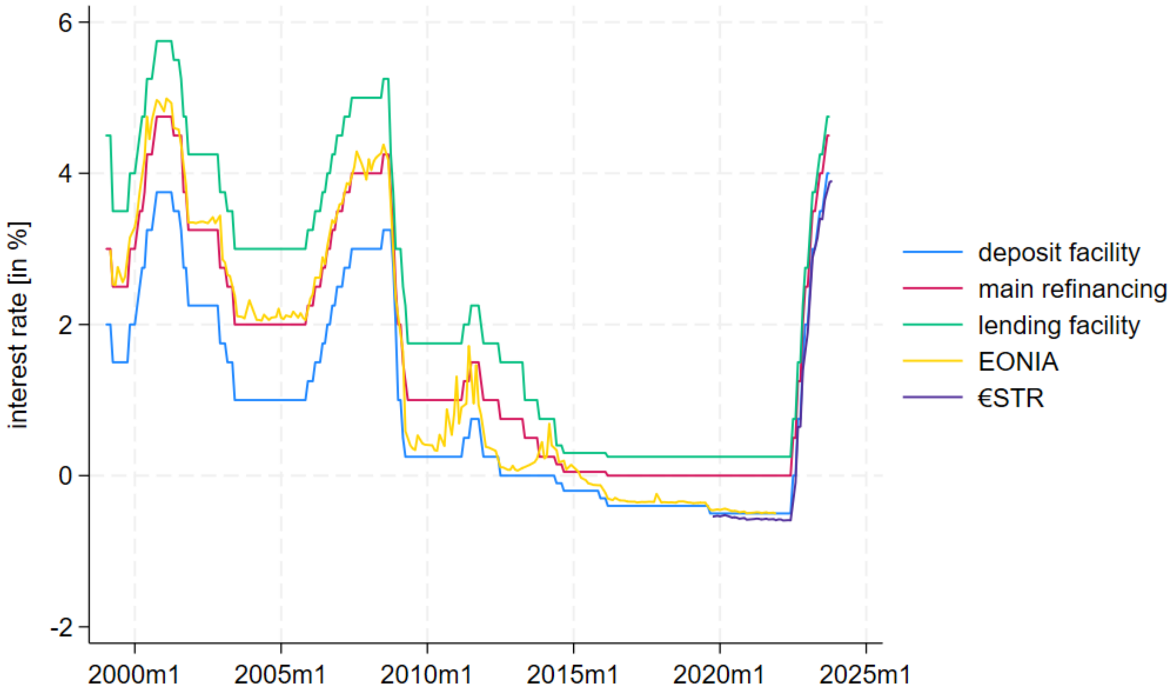


(a) Weighted by Matches

(b) Weighted by Volume

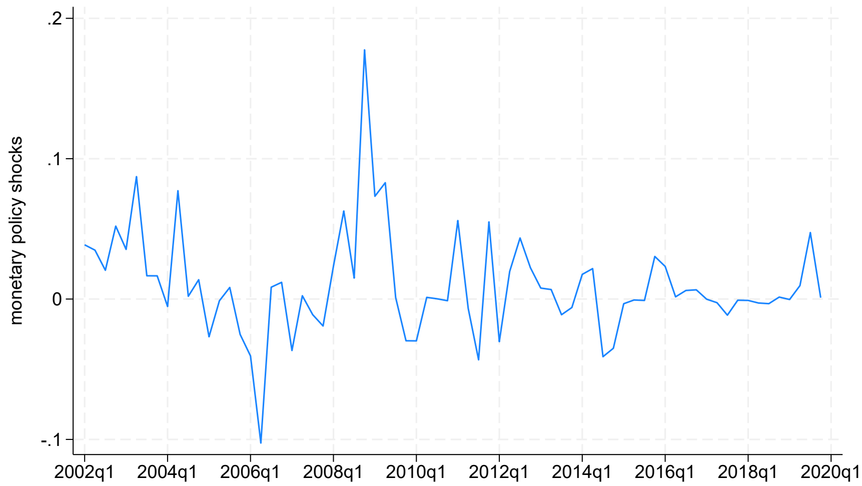
Notes: Bank-to-bank linkages in the German interbank market between 2002 and 2019. Size deciles of borrowers and size deciles of lenders are on the horizontal and vertical axes, respectively The intensity of lender-borrower matches is represented by the size of circles. Panel (a) weighs lender-borrower interactions by the number of matches, and panel (b) weights lender-borrower interactions by the volume of transactions.

Figure 4: Interest Rates



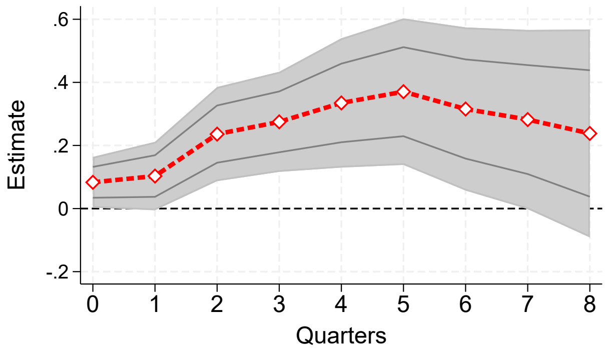
Notes: Time series of the deposit facility, main refinancing, lending facility, interbank (EONIA) and the euro short-term interest rates. Source: ECB.

Figure 5: Monetary Policy Shocks.

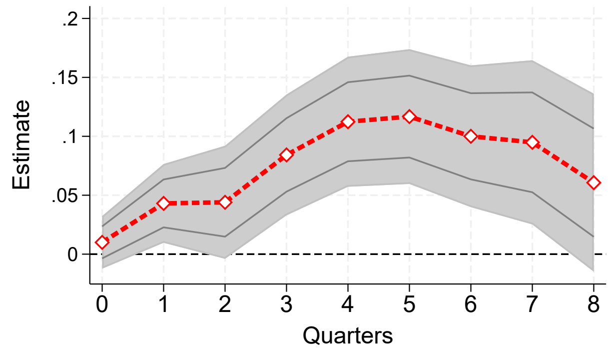


Notes: Monetary policy shock for the euro are, identified with the high-frequency identification approach. Source: Jarocinski and Karadi (2020).

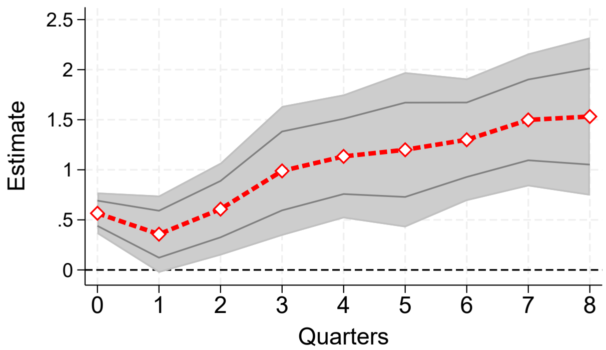
Figure 6: Local Projections



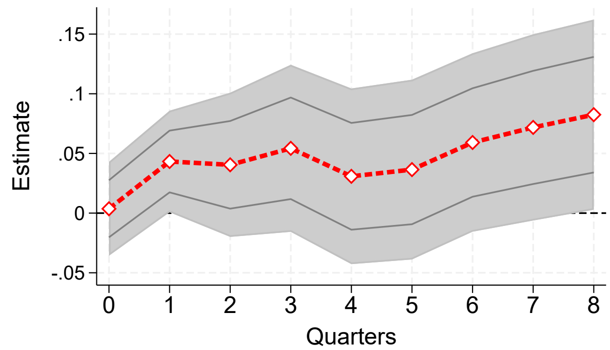
(a) Average Effect: Intensive Margin



(b) Average Effect: Extensive Margin



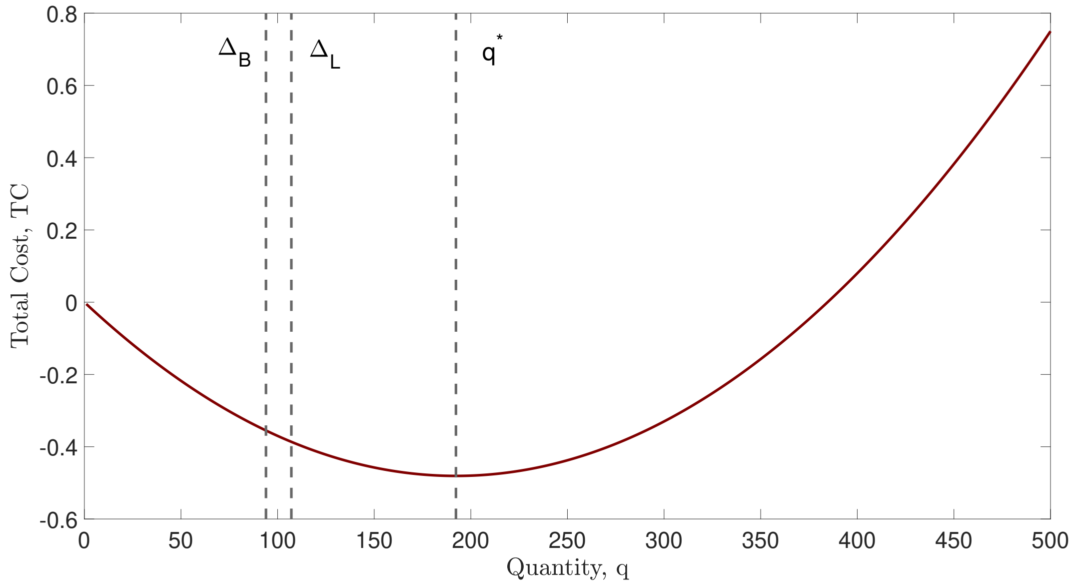
(c) Heterogeneous Effect: Intensive Margin



(d) Heterogeneous Effect: Extensive Margin

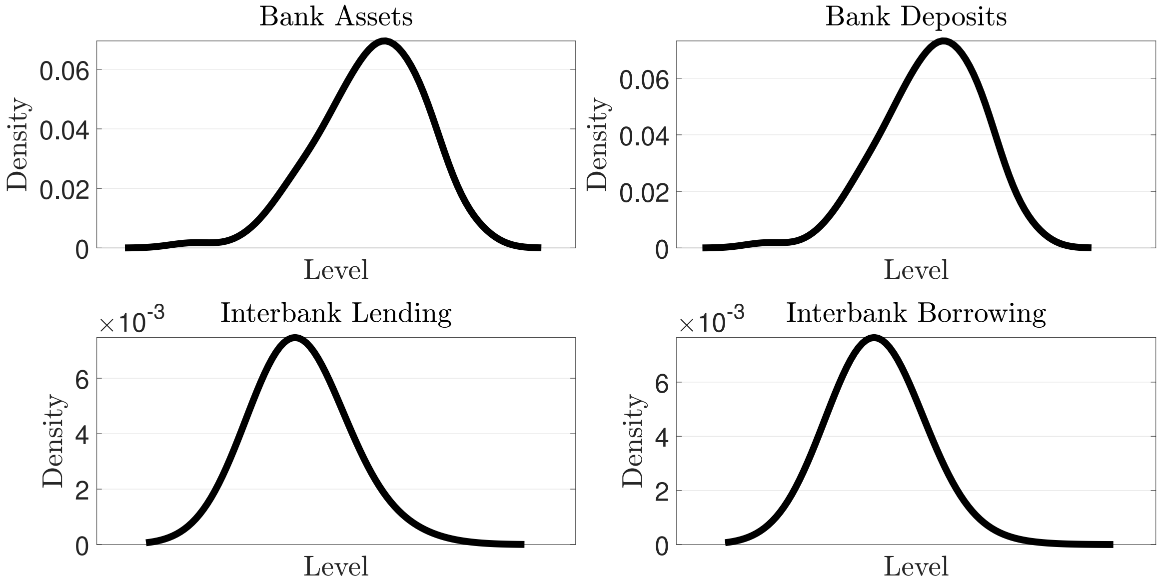
Notes: Local projections with respect to identified monetary policy shocks that are shown on Figure 5. The quarterly sample is 2002:q1-2019:q4. Gray lines and shaded areas correspond to 68% and 90% confidence intervals, respectively. Standard errors are three-way clustered at the year-quarter, lender, and borrower-levels.

Figure 7: Graphical Illustration of the Interbank Market



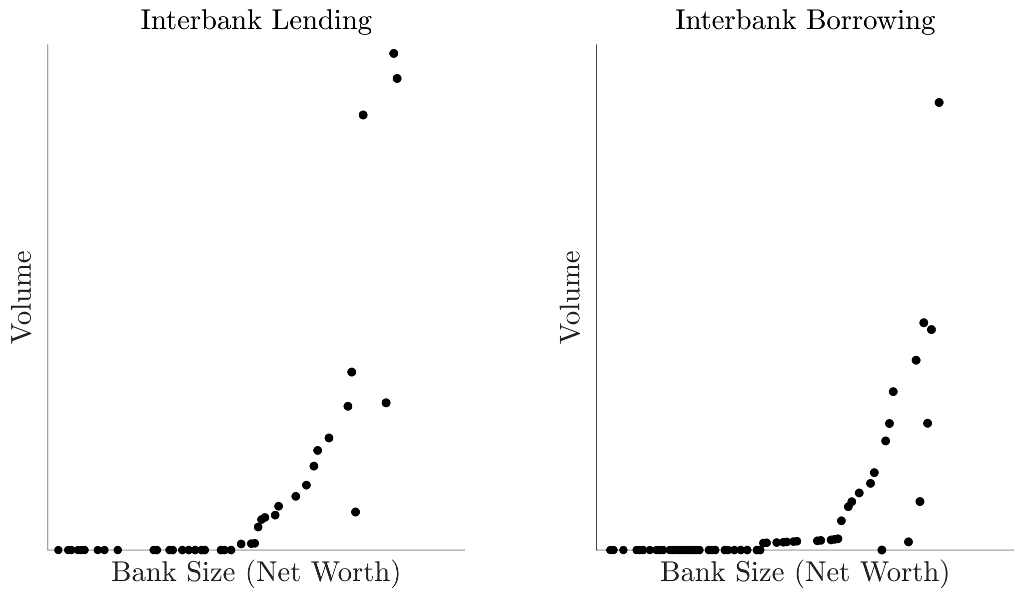
Notes: Illustration of the first round of the interbank market clearing mechanism in the model. Potential transaction quantity choices are on the horizontal axis. The total relative cost of borrowing from the first-ranked lender (TC) is on the vertical axis. q^* corresponds to the ideal quantity choice. Δ_L and Δ_B correspond to excess reserves of the first-ranked lender and (absolute value of) deficit reserves of the choosing borrower, respectively.

Figure 8: Select Stationary Distributions in the Model



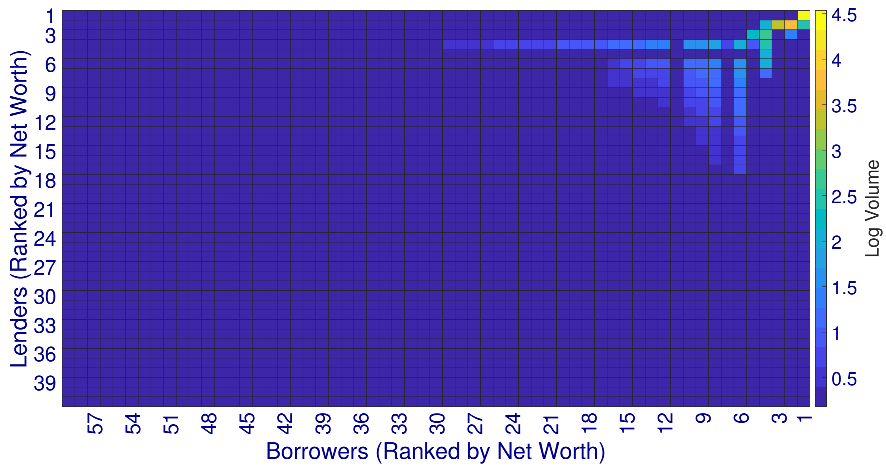
Notes: Stationary distributions of banks assets k_j, deposits b_j, interbank lending A_j^L, and interbank borrowing A_j^B from the stationary general equilibrium of the model.

Figure 9: Bank Size and the Interbank Market in the Model

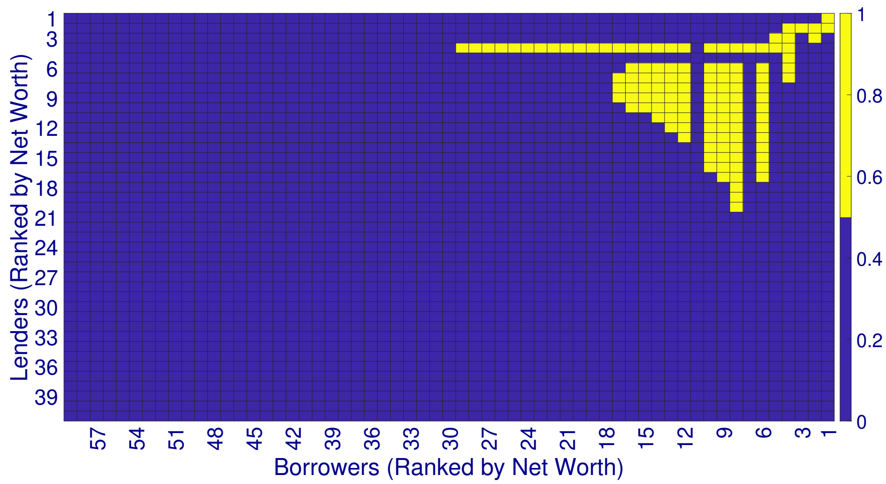


Notes: Model scatterplots of bank size (net worth) on the horizontal axis and total interbank lending and borrowing volumes on the vertical axes of the left and right panels, respectively. Scatterplots are produced based on the stationary equilibrium.

Figure 10: Assortative Matching in the Model



(a) Intensive Margin (Continuous Volume)

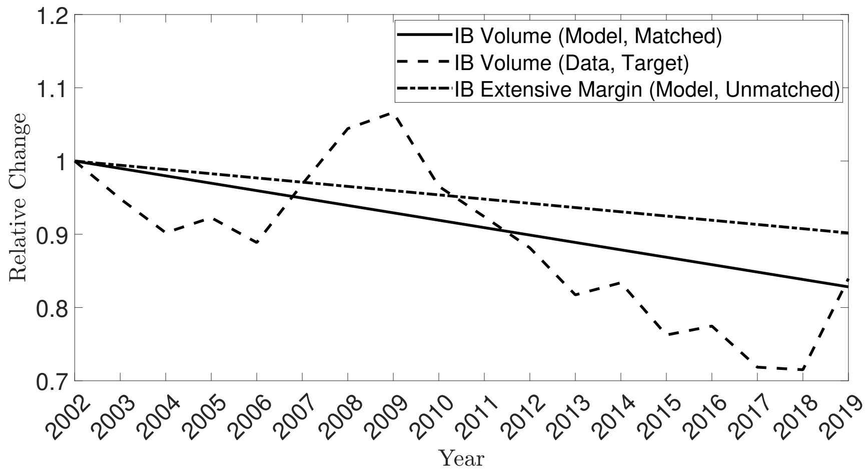


(b) Extensive Margin (Binary Indicator)

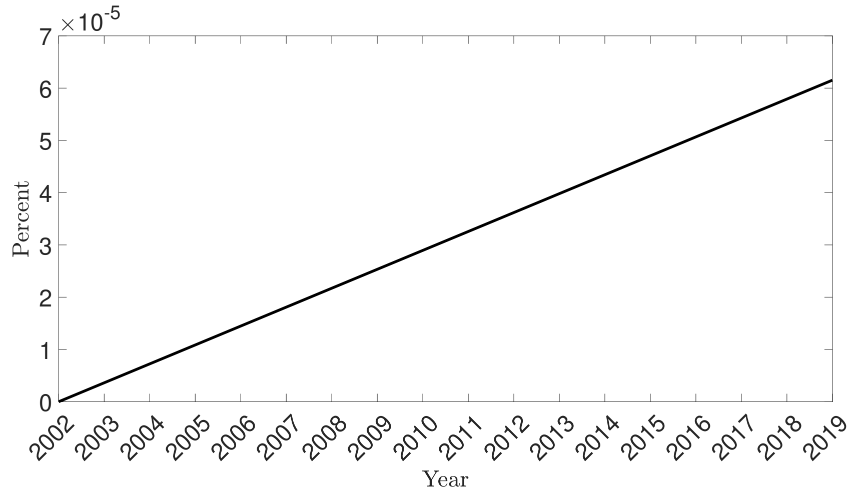
Notes: Bank-to-bank matching metrics in the model's interbank market. Borrowers that are ranked by net worth are on the horizontal axis. Lenders that are ranked by net worth are on the vertical axis. Panel (a) presents (log) volume of each transaction. Warmer shades correspond to greater volumes. Panel (b) shows the binary indicator which takes the value of unity if a match takes place and zero otherwise.

Figure 11: Secular Decline in Interbank Trading

(a) Quantities (Output)

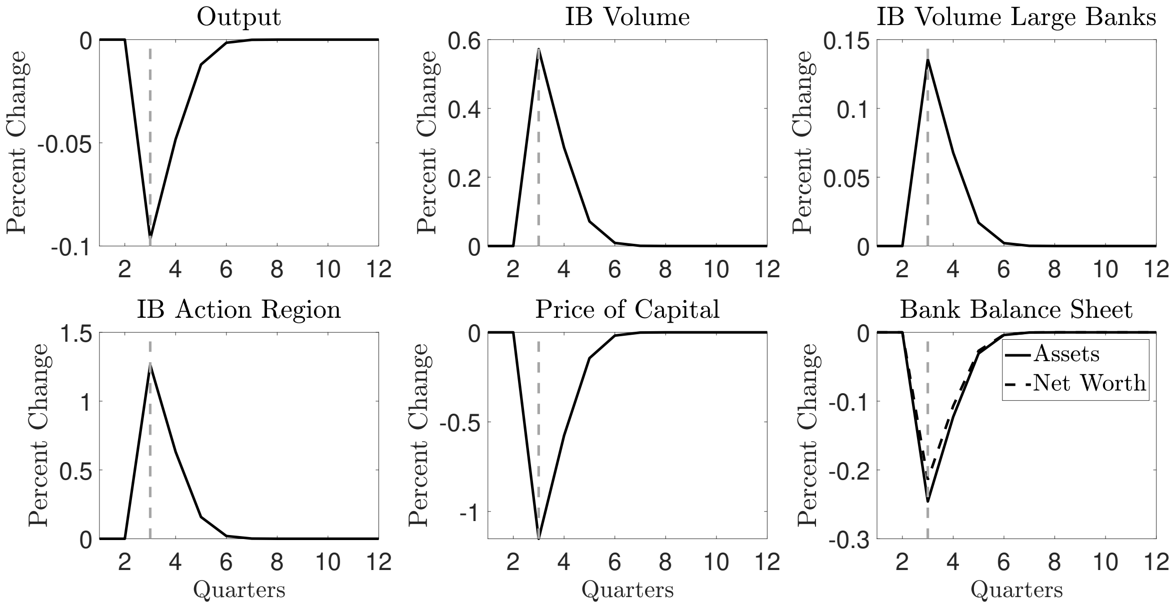


(b) Match Variable Cost (Input)



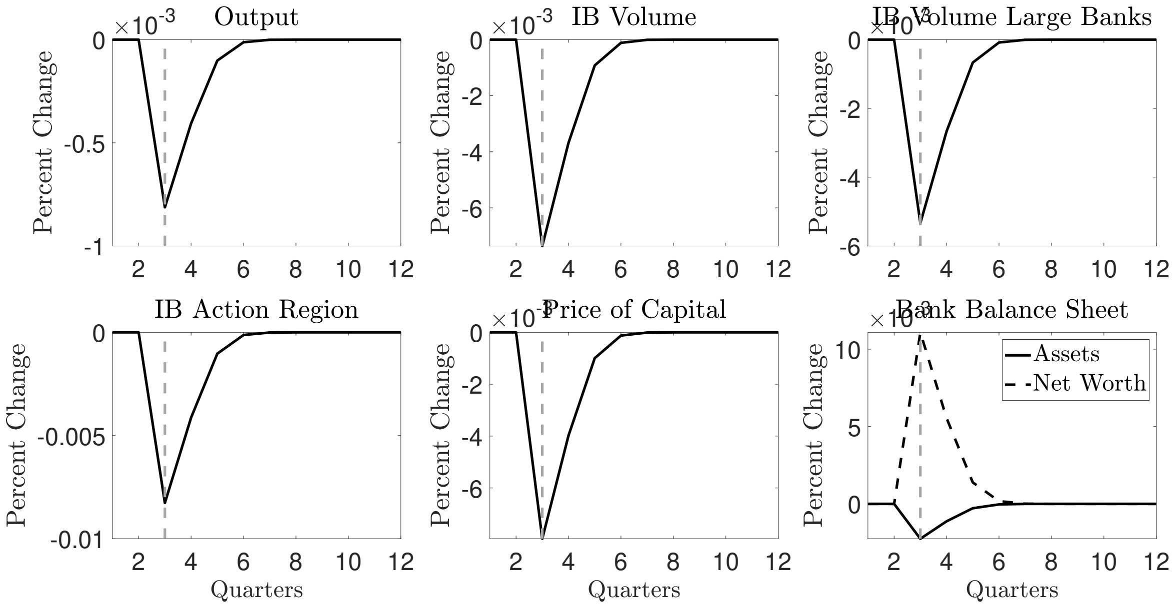
Notes: Trend-matching exercise in the model. Panel (b) shows the path of the interbank match variable cost parameter $\varphi_{1,t}$ that is the consistent with model-implied path of interbank-market volumes that matches the data. Panel (a) show the empirical target, the matched moment from the model, and the untargeted path of the extensive margin of the interbank market which is defined as the ratio of borrowers that are active in the market.

Figure 12: Impulse Response to a Contractionary Monetary Shock



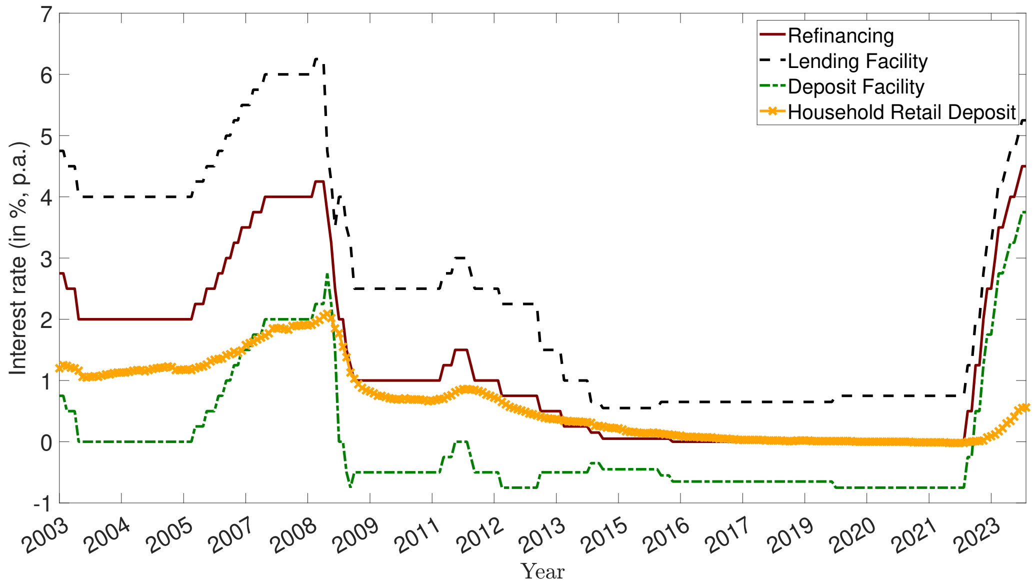
Notes: Model impulse responses with respect to a contractionary monetary policy shock, defined as a simultaneous 2.4% p.a. increase in the refinancing rate and the 1.5% p.a. widening of the interest rate corridor spread. The shocks hit the economy in period 3 and revert back to steady-state levels with the autocorrelation rate of 0.5.

Figure 13: Impulse Response to Higher Reserve Requirements



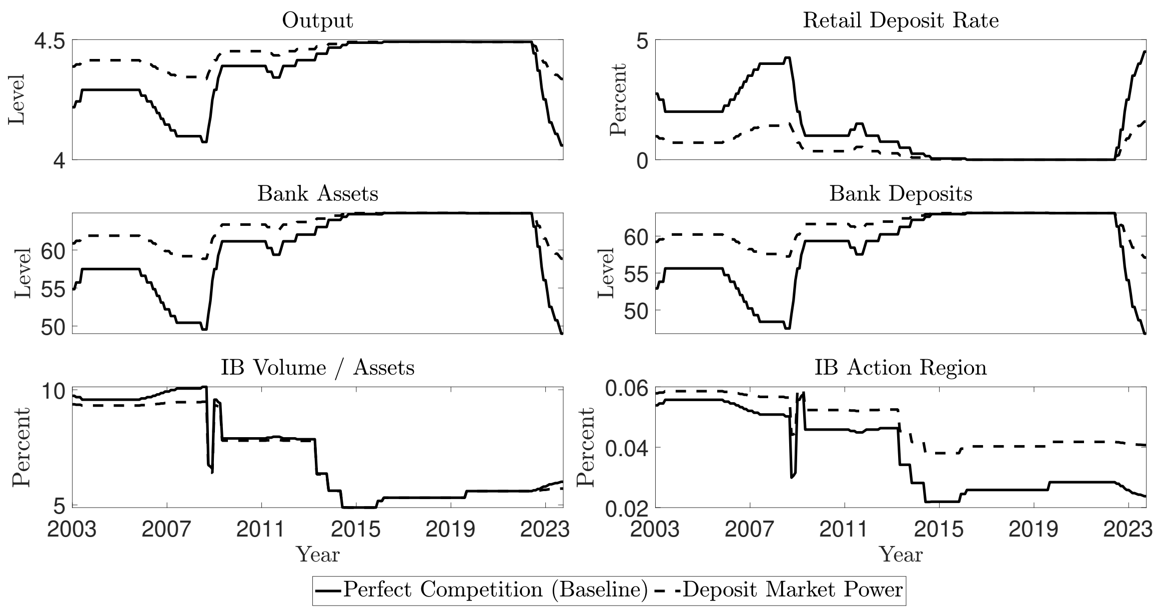
Notes: Model impulse responses with respect to a contractionary liquidity policy shock, defined as a 1.65% increase in the minimum reserves requirement ratio starting from the steady state with no minimum reserves. The shock hits the economy in period 3 and revert back to steady-state levels with the autocorrelation rate of 0.5.

Figure 14: Retail Deposit Rates and the Policy Corridor



Notes: Time series of the average German retail household deposit interest rate along with the ECB refinancing, lending facility, and deposit facility rates. Source: Bundesbank and ECB.

Figure 15: The Role of Deposit Market Power



Notes: model simulations under perfect and imperfect deposit market competition assumptions. Inputs include the exact time series of the ECB interest rate corridor involving the refinancing, lending facility, and deposit facility rates.

Tables

Table 1: Summary Statistics

Panel A: Interbank market level (2002q2-2019q4)	Mean	SD	p25	p75	*N*
Number of borrowers	1,779	215	1,643	1,911	71
Number of lenders	1,852	219	1,711	1,983	71
Number of loans	28,251	27,484	24,084	32,163	71
New links	1,740	748	1,247	2,045	71
Terminated links	1,451	575	1,026	1,701	71
Panel B: Bank level (2010q4)	Mean	SD	p25	p75	*N*
Assets [€ mn.]	4,307	32,270	200	1,490	1,844
Non-bank lending / assets	0.552	0.172	0.474	0.657	1,844
Bank lending / assets	0.139	0.144	0.059	0.162	1,844
Non-bank funding / assets	0.684	0.170	0.653	0.781	1,844
Bank funding / assets	0.164	0.141	0.083	0.201	1,844
Capital / assets	0.064	0.065	0.046	0.065	1,844
Profits / assets	0.035	0.042	0.028	0.035	1,844
Market share [in %]	0.054	0.468	0.002	0.017	1,844

Notes: This table provides basic summary statistics for main variables used in the empirical analysis.

Table 2: Lender-Borrower Matching on the Interbank Market

	$Match_{bct}$		$Match_{bct}^{weighted}$	
Entity_{bt} :	Top lender	Top borrower	Top lender	Top borrower
	(1)	(2)	(3)	(4)
$\text{Entity}_{bt} \times 2^{\text{nd}}$ decile counterparty_{ct}	0.001*	0.012***	0.014**	0.088***
	(0.001)	(0.002)	(0.007)	(0.017)
$\text{Entity}_{bt} \times 3^{\text{rd}}$ decile counterparty_{ct}	0.002*	0.024***	0.026**	0.188***
	(0.001)	(0.004)	(0.012)	(0.031)
$\text{Entity}_{bt} \times 4^{\text{th}}$ decile counterparty_{ct}	0.004**	0.037***	0.043***	0.283***
	(0.002)	(0.006)	(0.016)	(0.045)
$\text{Entity}_{bt} \times 5^{\text{th}}$ decile counterparty_{ct}	0.006***	0.048***	0.061***	0.380***
	(0.002)	(0.007)	(0.017)	(0.058)
$\text{Entity}_{bt} \times 6^{\text{th}}$ decile counterparty_{ct}	0.008***	0.056***	0.079***	0.453***
	(0.002)	(0.008)	(0.021)	(0.069)
$\text{Entity}_{bt} \times 7^{\text{th}}$ decile counterparty_{ct}	0.013***	0.064***	0.117***	0.537***
	(0.004)	(0.010)	(0.030)	(0.083)
$\text{Entity}_{bt} \times 8^{\text{th}}$ decile counterparty_{ct}	0.019***	0.077***	0.168***	0.670***
	(0.005)	(0.012)	(0.046)	(0.106)
$\text{Entity}_{bt} \times 9^{\text{th}}$ decile counterparty_{ct}	0.032***	0.095***	0.273***	0.857***
	(0.007)	(0.014)	(0.066)	(0.132)
$\text{Entity}_{bt} \times 10^{\text{th}}$ decile counterparty_{ct}	0.120***	0.156***	1.210***	1.508***
	(0.014)	(0.017)	(0.141)	(0.171)
N	58,767,439	58,767,439	58,767,439	58,767,439
R^2	0.326	0.333	0.323	0.330
Lender-Year FE	✓	✓	✓	✓
Borrower-Year FE	✓	✓	✓	✓
SE Cluster	Lender and Borrower			

Notes: The sample is a filled panel for all possible combinations at the bank-counterparty-year level *bct* from 2002 to 2019. $Entity_{bt}$ is an indicator variable for a lender b in the top decile ("Top lender" in columns 1 and 3) or borrower b in the top decile ("Top borrower" in columns 2 and 4). As such, $Counterparty_{ct}$ refers to borrowers in columns 1 and 3, and to lenders in columns 2 and 4. We generate separate indicator variables for counterparties according to their position in the size distribution in year t, with the bottom decile being the omitted category. The dependent variable in columns 1 and 2, $Match_{bct}$, equals 1 in case of a relationship between lender and borrower in a given year t, and 0 otherwise. The dependent variable in columns 3 and 4, $Match_{bct}^{weighted}$, is defined as $Match_{bct} \times \ln(Volume)_{bct}$, where $Volume_{bct}$ is the exposure between lender and borrower in a given year t. Standard errors (in parentheses) are double-clustered at the lender and borrower level.

Table 3: Model Parameterization

Parameter	Value	Description	Target/Source
		Macro	
α	0.36	Production function	Standard
β	0.995	Discount factor	Refinancing rate = 2% p.a.
ϕ	1	Risk Aversion	Standard
δ	1	Capital Depreciation	Standard
		Interbank Market	
$\underline{q}$	1.2	Minimum quantity cutoff	Target region of inaction = 5%
ψ_1	1.3e-5	Match variable cost, linear	Target size-IB borrowing elasticity = 0.55
ψ_2	2	Match variable cost, quadratic	Normalization
		Bank Balance Sheets	
σ_κ	0.042	Permanent heterogeneity volatility	Standard deviation of returns on assets = 4.2%
σ	0.973	Dividend payout frequency	Gertler and Kiyotaki (2010)
ν_1	0.0004	Non-interest expense, linear	Target non-interest expense to assets ratio = 1.9%
ν_2	2	Non-interest expense, quadratic	Normalization
σ_ξ	1.55	Stochastic deposit withdrawal volatility	Target interbank market loans to assets ratio = 13%
λ	0.1	Capital requirement ratio	Target assets to equity ratio = 11
		Policy	
ω	1.62%	Reserve Requirement Ratio	ECB, average across years
R^S	1.287%	Interest Rate on Reserves, percent p.a.	ECB, average across years
S	1.23%	Interest Corridor Spread, percent p.a.	ECB, average across years

Notes: This table summarizes calibration of the baseline model.

Table 4: Model Steady States

	Baseline	No IB Match Cost	No IB Quantity Cutoff	Low Volatility
IB Volume	496.35	2577.21	894.36	0.00
IB Volume Largest Banks	342.74	545.35	342.30	0.00
IB Fraction of Matches Active	0.05	0.04	0.56	0.00
IB Fraction of Borrowers Active	0.47	0.88	1.00	0.00
Bank Assets	48.67	49.20	48.76	49.12
Bank Net Worth	4.68	4.90	4.74	4.31
Bank Deposits	46.60	46.95	46.64	47.43
Market Leverage Ratio	11.10	10.64	10.96	12.12
Price of Capital	1.04	1.04	1.04	1.04
Aggregate Output	4.05	4.07	4.05	4.06
Aggregate Consumption	4.98	5.02	4.99	5.00

Notes: This table summarizes key financial and economic aggregates from various stationary steady states. The first column reports results from the baseline economy. Columns 2, 3, and 4 report results from the cases with $\varphi_1 = 0$, $\underline{q} = 0$, and $\sigma_\xi = 1e-4$, respectively.