A Dynamic Network Model of the Unsecured Interbank Lending Market[1]

Francisco Blasques[a] Falk Bräuning[b] Iman van Lelyveld[a,c]

[a]VU University Amsterdam
[b]Federal Reserve Bank of Boston
[c]De Nederlandsche Bank

The Role of Liquidity in the Financial System
Atlanta, November 19th, 2015

[1]The views expressed in this presentation do not necessarily represent those of the Federal Reserve Bank of Boston, the Federal Reserve System, De Nederlandsche Bank, or the Eurosystem.

This Paper in a Nutshell

- Model of **formation of interbank lending relationships**, implications for credit availability and conditions (interest rates and volumes)

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- **Parameter estimation** using Dutch interbank loan-level data 2008-2011
- **Model analysis**: network structure, dynamic behavior and monetary policy

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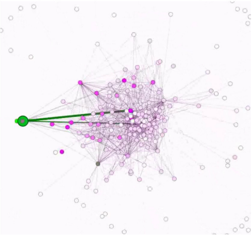
Dutch Interbank Market during Crisis



Before Lehman 08/2008

Figure : **Nodes:** banks; **links:** ON loans; **big green node:** central bank; **small green nodes:** banks only relying on central bank; **pink nodes:** banks without use of central bank facilities, see Video 3 Heijmans et al. (2014)

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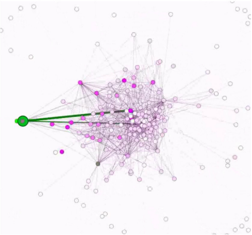

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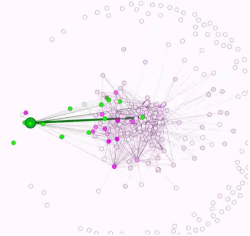

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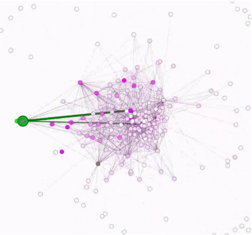

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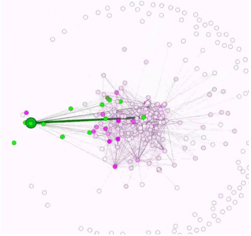

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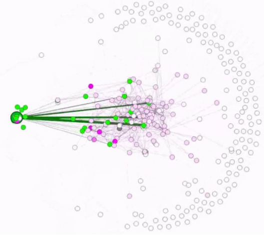

After 3-yr LTRO 12/2011

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Relevance of Private Information

- Why should central banks not resume the role of central counterparty for money market transactions also in normal times (i.e. non-crisis times)?

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- Efficiency of liquidity allocations, Rochet & Tirole (1996)

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→ **Key issue**: Role of credit risk uncertainty, peer monitoring and private information in the interbank market? In OTC market we need to consider uncertainty as bank-to-bank specific problem!

Preview of Main Results

- Network model of credit risk uncertainty and peer monitoring **explains two stylized facts** of decentralized interbank lending markets
  - **Sparse core-periphery structure** of lending network
  - Stable long-term trading relationships, **relationship lending**

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  - **Trading more concentrated** towards bank pairs with strong relations
- Monetary policy implication for size of **interest rate corridor**
  - wider corridor increases interbank lending (direct effect on outside options)
  - indirect **multiplier effect** through changes in monitoring and search

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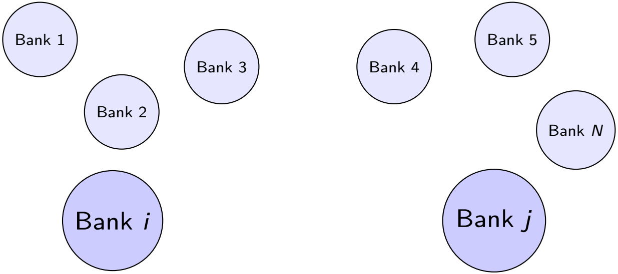
A Model of Bilateral Link Formation



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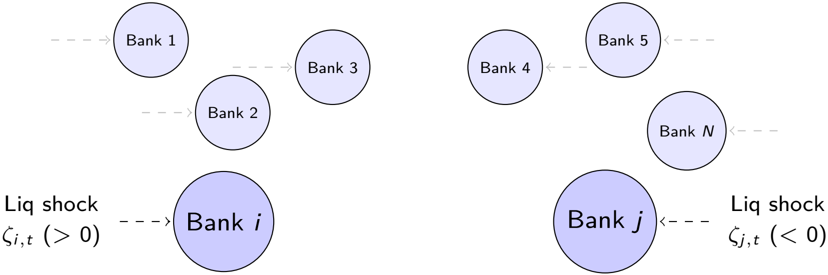

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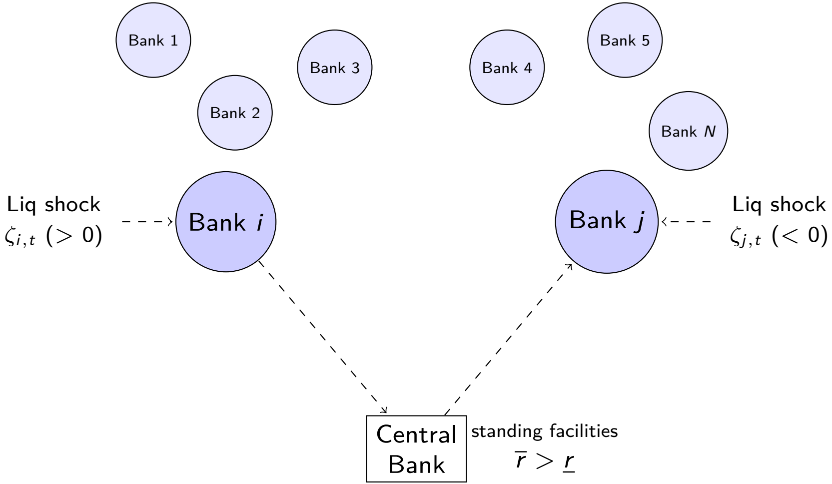

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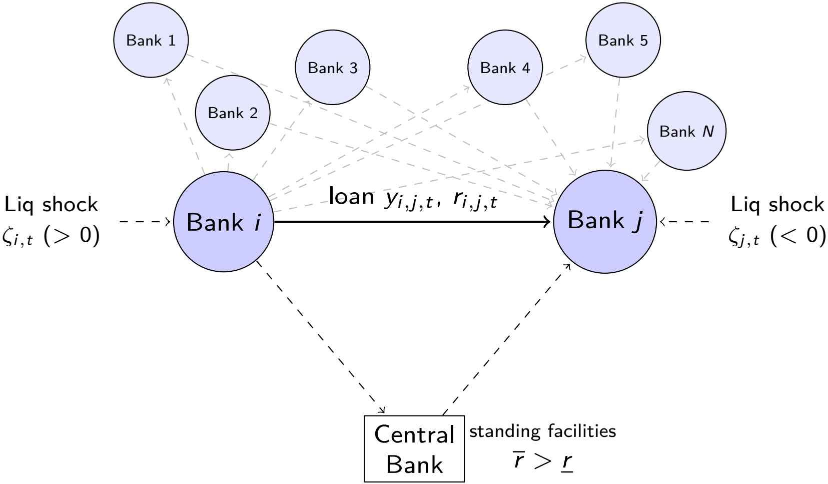

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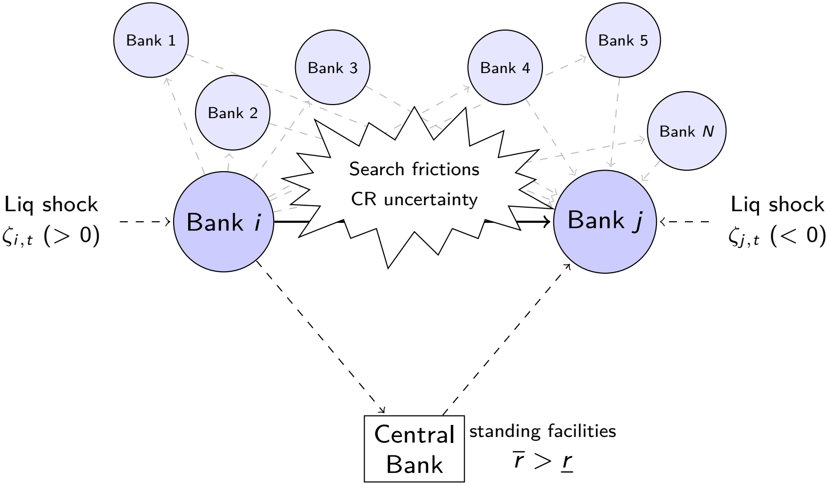

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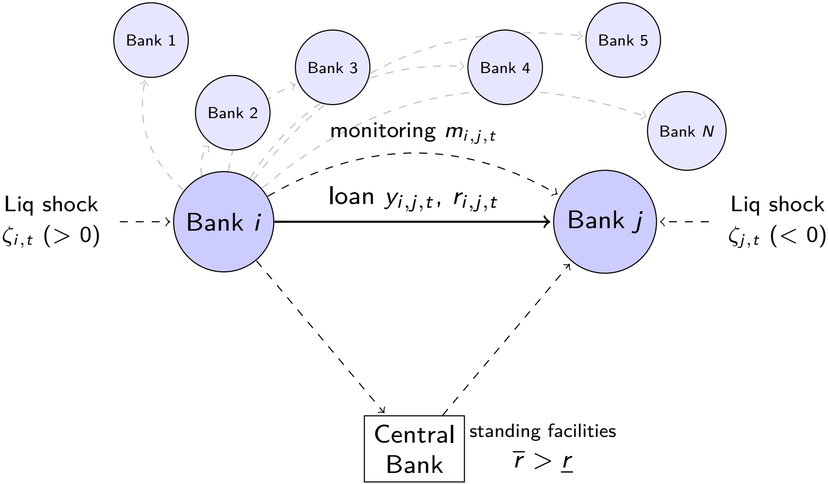

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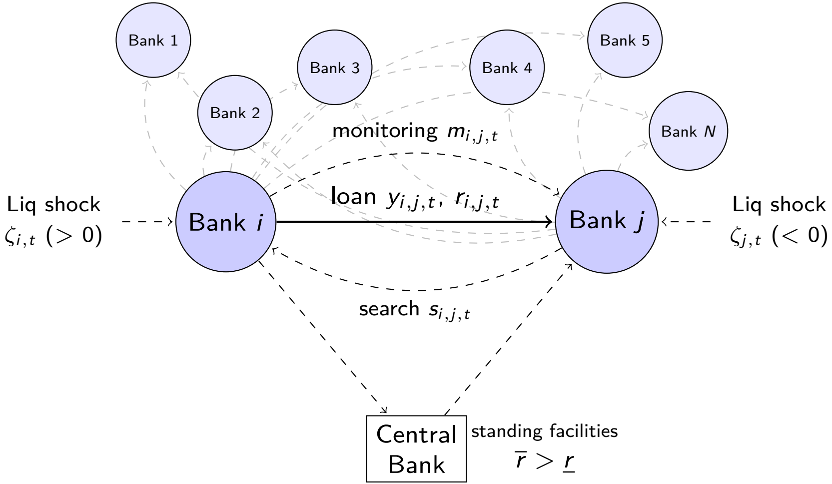

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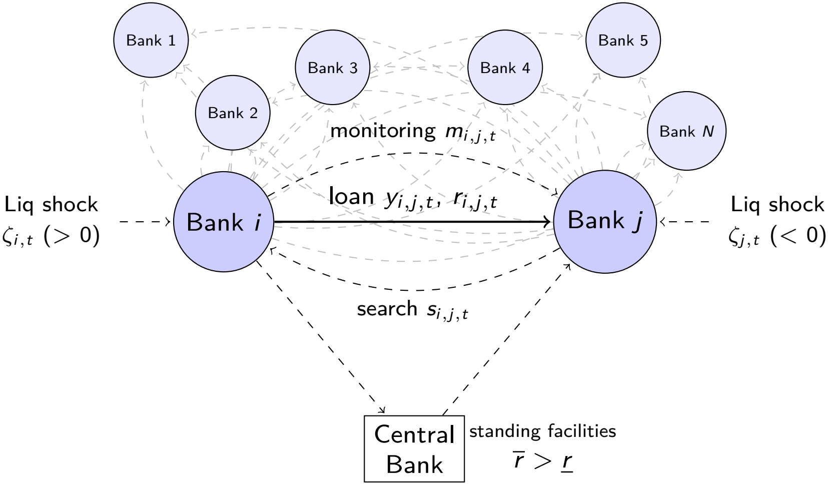

Model Perspective

- Model focuses on **formation of bilateral lending relationships** under credit risk uncertainty and search frictions
  - **peer monitoring** and **directed search**
- Model **does not** take into account for:
  - endogenous true riskiness (unrelated to uncertainty, liquidity shocks, monitoring)
  - other assets/liabilities (treasury perspective)
  - serial correlation in liquidity shocks, common factors
  - other monetary policy instruments than standing facilities (MROs, LTROs)
  - liquidity hoarding for precautionary reasons
  - bank heterogeneity other than in liquidity shocks (default risk, bargaining power)

Liquidity Shocks

- Banks are hit by exogenous liquidity shocks $\zeta_{i,t}$

$$\zeta_{i,t} \overset{iid}{\sim} \mathcal{N}(\mu_{\zeta_i}, \sigma^2_{\zeta_i}) \quad \text{where } \mu_{\zeta_i} \sim \mathcal{N}(\mu_\mu, \sigma^2_\mu) \text{ and } \log \sigma_{\zeta_i} \sim \mathcal{N}(\mu_\sigma, \sigma^2_\sigma)$$

  and correlation parameter $\rho_\zeta := corr(\mu_{\zeta_i}, \log \sigma_{\zeta_i})$

- Heterogeneity related to scale of bank's business (σ_{ζ_i}) and structural liquidity deficit or surplus (μ_{ζ_i})

Credit Risk Uncertainty and Peer Monitoring

- Perceived financial distress: $z_{i,j,t} = z_{j,t} + e_{i,j,t}$
  - $z_{j,t} \sim (0, \sigma^2)$ is true financial distress of j, true PD: $\mathbb{P}(z_{j,t} > \epsilon)$
  - $e_{i,j,t} \sim (0, \tilde{\sigma}^2_{i,j,t})$ is independent perception error

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- Perceived probability of default

$$\mathbb{P}(z_{i,j,t} > \epsilon) \leq \frac{\sigma^2 + \tilde{\sigma}^2_{i,j,t}}{\sigma^2 + \tilde{\sigma}^2_{i,j,t} + \epsilon^2} =: P_{i,j,t}$$

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- Evolution of $\tilde{\sigma}^2_{i,j,t}$ (credit risk uncertainty)

$$\log \tilde{\sigma}^2_{i,j,t+1} = \alpha_\sigma + \gamma_\sigma \log \tilde{\sigma}^2_{i,j,t} - \beta_\sigma m_{i,j,t} + u_{i,j,t}, \quad u_{i,j,t} \sim \mathcal{N}(0, \sigma_u^2)$$

where $m_{i,j,t}$ is bank-to-bank monitoring expenditure

Link Formation, Interest Rates and Loan Volumes

- $B_{i,j,t} \sim \mathrm{Bernoulli}(\lambda_{i,j,t})$ indicates link between bank i and j at time t with

$$\lambda_{i,j,t} = \frac{1}{1 + \exp(-\beta_\lambda(s_{j,i,t} - \alpha_\lambda))}$$

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- If $B_{i,j,t} = 1$, bilateral Nash bargaining about rates

$$r_{i,j,t} = \theta r + (1-\theta)\frac{P_{i,j,t}}{1 - P_{i,j,t}}$$

where θ is bargaining power of lender, with $\overline{r} = r > \underline{r} = 0$ details

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- If $r_{i,j,t} \in [0, r]$, loan granted ($l_{i,j,t} = 1$) with exogenous volume

$$y_{i,j,t} = \min\{\zeta_{i,t}, -\zeta_{j,t}\}\mathbb{I}(\zeta_{i,t} \geq 0)\mathbb{I}(\zeta_{j,t} \leq 0),$$

  where $\zeta_{i,t}$ and $\zeta_{j,t}$ are liquidity shocks specific to each transaction

Dynamic Optimization Problem

- Dynamic optimization problem of each bank i:

$$\max_{\{m_{i,j,t}, s_{i,j,t}\}} \mathbb{E}_t \sum_{s=t}^{\infty} \left(\frac{1}{1+r^d}\right)^{s-t} \sum_{j=1}^{N} (l_{i,j,t}\bar{R}_{i,j,t}y_{i,j,t} + l_{j,i,t}(r - r_{j,i,t})y_{j,i,t} - m_{i,j,t} - s_{i,j,t})$$

s.t. constraints; where $\bar{R}_{i,j,t} = (1 - P_{i,j,t})r_{i,j,t} - P_{i,j,t}$, no default occurs!

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- Linearized policy function for **optimal monitoring**

$$m_{i,j,t} = a + b\tilde{\sigma}^2_{i,j,t} + c\mathbb{E}_t\tilde{\sigma}^2_{i,j,t+1} + d\mathbb{E}_t y_{i,j,t+1} + e\mathbb{E}_t B_{i,j,t+1}$$

- Non-linear policy function for **optimal search**

$$s_{i,j,t} = h(\mathbb{E}_t(r - r_{j,i,t})y_{j,i,t}) \qquad h(\cdot)' \geq 0$$

Dynamic Optimization Problem

- Dynamic optimization problem of each bank i:

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- Non-linear policy function for **optimal search**

$$s_{i,j,t} = h(\mathbb{E}_t(r - r_{j,i,t})y_{j,i,t}) \qquad h(\cdot)' \geq 0$$

- Adaptive expectations of $x_{i,j,t}$ using exponentially weighted moving average

$$\mathbb{E}_t x_{i,j,t+1} =: x^*_{i,j,t} = (1 - \lambda_x)x^*_{i,j,t-1} + \lambda_x B_{i,j,t} x_{i,j,t}$$

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Data Characterization Using Network Statistics

- Observed variables are $\boldsymbol{l_{i,j,t}}$ (**link/loan indicator**), $\boldsymbol{y_{i,j,t}}$ (**volumes**) and $\boldsymbol{r_{i,j,t}}$ (**spreads**), for unsecured overnight loans between $N = 50$ Dutch banks from 01-02-2008 to 30-04-2011 ($T = 810$)
- At each t, we compute statistics of trading network implied by $\{l_{i,j,t}\}$, with link weights $\{y_{i,j,t}\}, \{r_{i,j,t}\}$ to characterize network topology

Statistic	Interpretation
Density	Fraction of existing trading relations (links) relative to all potential relations
Reciprocity	Fraction of reciprocal relationships among all existing trading relationships
Stability	Fraction of relationships that did not change as compared to previous network
Degree Centrality	In- and out-degree of node: number of different lenders/borrowers per bank $\rightarrow$ cross-sectional degree distribution
Clustering	How close are a node's neighbors are to being a clique (complete network) $\rightarrow$ average distribution as global measure
$Corr(l_{i,j,t}, \#l^{rw}_{i,j,t-1})$	Stability of bilateral trading relationship
$Corr(r_{i,j,t}, \#l^{rw}_{i,j,t-1})$	Price impact of intensity of bilateral relationship (relationship lending)

- From dynamic lending network we obtain **sequences of network statistics**

Indirect Inference Estimator of Network Model

- **Idea**: characterize data X by vector of auxiliary statistics β in a way that identifies structural parameters θ, then simulate $s = 1, ..., S$ different datasets X_s and choose $\hat{\theta}$ as

$$\hat{\theta} := \underset{\theta \in \Theta}{\operatorname{argmin}} \|\hat{\beta}(X) - \frac{1}{S} \sum_{s=1}^{S} \hat{\beta}(X_s(\theta))\|.$$

- Indirect inference estimator $\hat{\theta}$ is consistent and asymptotically normal, see Gouriéroux et al. (1993)

- Moments of sequence of network statistics and moments of bilateral volumes and spreads as auxiliary statistics, see Blasques and Bräuning (2014) details

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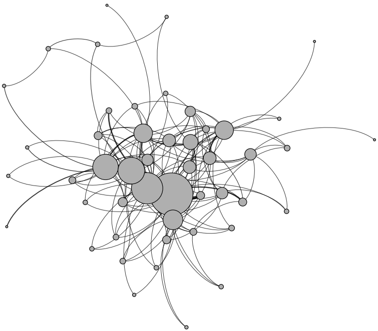
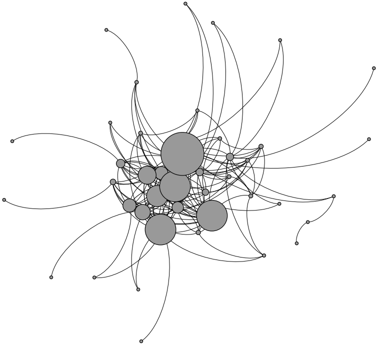
Observed and Simulated Lending Network



(a) Observed network



(b) Simulated network (under $\hat{\boldsymbol{\theta}}_T$)

Figure : Interbank network during one week. Nodes are scaled according to total trading volume.

Comparison of Auxiliary Statistics

Auxiliary statistic (mean)	Observed $\hat{\beta}_T$	Simulated $\tilde{\beta}_{TS}(\hat{\theta}_T)$
Density	0.021	0.020
Reciprocity	0.082	0.060
Avg clustering	0.031	0.035
Stability	0.982	0.978
...		

details

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$\mathrm{Corr}(l_{i,j,t}, \# l^{rw}_{i,j,t-1})$	0.644	0.586
$\mathrm{Corr}(r_{i,j,t}, \# l^{rw}_{i,j,t-1})$	-0.072	-0.123
...		

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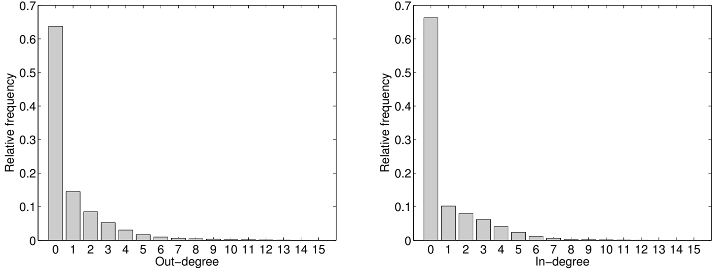
...		
Avg log volume	4.117	4.137
Std log volume	1.690	1.136
Avg spread	0.286	1.075
Std spread	0.107	0.112

details

Simulated Degree Distributions



(a) Out-degree (# borrowers) (b) In-degree (# lenders)

Auxiliary statistic (mean)	Observed $\hat{\beta}_T$	Simulated $\tilde{\beta}_{TS}(\hat{\theta}_T)$
Avg degree	1.038	0.991
Std outdegree	1.841	1.753
Skew outdegree	2.882	2.451
Std indegree	1.600	1.687
Skew indegree	2.403	2.076

Parameter Estimates: What Drives the Lending Patterns?

- 16 structural parameters estimated, 8 calibrated (not identified) details
- Some key results:

Economic hypothesis	H_0	$\hat{\theta}$	reject at 1%
Monitoring has no effect on information	$\beta_\sigma = 0$	9.662	Yes
Search has no effect on link probability	$\beta_\lambda = 0$	72.83	Yes
No liquidity shock heterogeneity in mean	$\sigma_\mu^* = 0$	1.990	Yes
No liquidity shock heterogeneity in variance	$\sigma_\sigma = 0$	1.981	Yes

- Linear policy rule for monitoring:

Variable	CR Uncertainty $\tilde{\sigma}_{i,j,t}$	$\mathbb{E}_t\tilde{\sigma}_{i,j,t+1}$	Link $\mathbb{E}_t B_{i,j,t+1}$	Volume $\mathbb{E}_t y_{i,j,t+1}$
Coefficient	0.002	-0.0055	0.0383	0.0014

- Persistent expectations about bilateral link probabilities ($\lambda_B = 0.93$) and volumes ($\lambda_y = 0.85$), less for spreads ($\lambda_r = 0.41$)

Heterogeneous Liquidity Shock Distributions

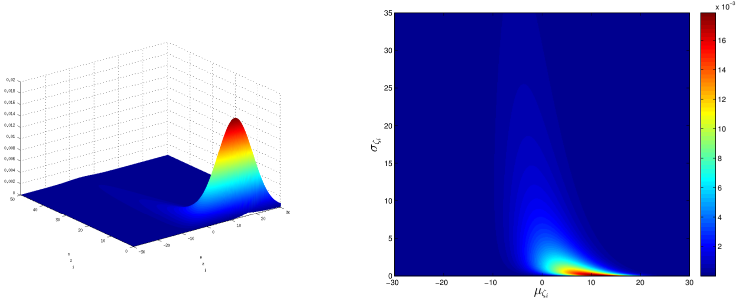
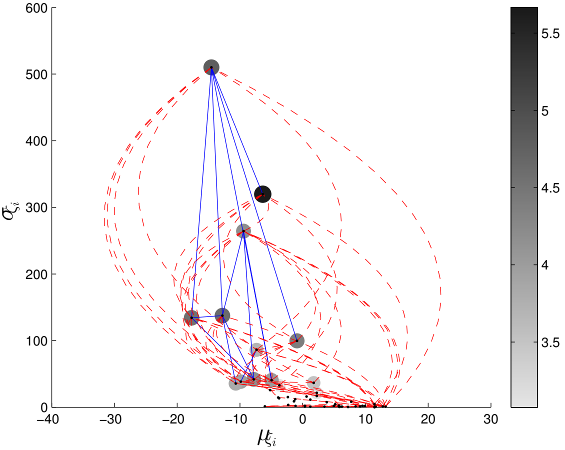


Figure : Joint distribution of mean and standard deviation parameter

$$\zeta_{i,t} \sim \mathcal{N}(\mu_{\zeta_i}, \sigma^2_{\zeta_i}) \quad \text{where} \quad \begin{pmatrix} \mu_{\zeta_i} \\ \log \sigma_{\zeta_i} \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} \mu_\mu \\ \mu_\sigma \end{pmatrix}, \begin{pmatrix} \sigma^2_\mu & \rho\sigma_\sigma\sigma_\mu \\ \rho\sigma_\sigma\sigma_\mu & \sigma^2_\sigma \end{pmatrix} \right)$$

Heterogeneous Liquidity Shocks and Trading Relationships



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Role of Peer Monitoring on Lending Structure

- Comparison with **no monitoring calibration** $\hat{\boldsymbol{\theta}}_A$, where $\beta_\sigma = 0$, and all other parameters fixed at estimated values $\hat{\boldsymbol{\theta}}_U$
- And comparison with **restricted estimates** $\hat{\boldsymbol{\theta}}_R$, where $\beta_\sigma = 0$, and all other parameters re-estimated

Auxiliary statistic (mean)	Calibrated $\tilde{\boldsymbol{\beta}}_{TS}(\hat{\boldsymbol{\theta}}_A)$	Restricted Estimation $\tilde{\boldsymbol{\beta}}_{TS}(\hat{\boldsymbol{\theta}}_R)$	Unrestricted Estimation $\tilde{\boldsymbol{\beta}}_{TS}(\hat{\boldsymbol{\theta}}_U)$	Observed $\hat{\boldsymbol{\beta}}_T$
$\mathrm{Corr}(l_{i,j,t}, l^{rw}_{i,j,t-1})$	0.2345	0.4259	0.6001	0.6439
$\mathrm{Corr}(r_{i,j,t}, l^{rw}_{i,j,t-1})$	0.0000	-0.1578	-0.1231	-0.0716
Skew outdegree	0.4512	1.3604	2.3649	2.8821
Skew indegree	0.3300	1.3971	2.2801	2.4030

Dynamic Network Responses to Credit Risk Uncertainty Shock

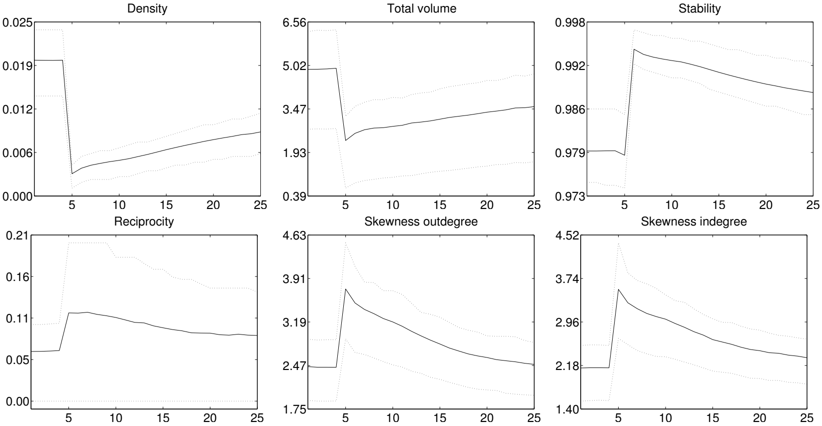


Figure : Simulated network responses to common shock to credit risk uncertainty

Responses of Monitoring and Search

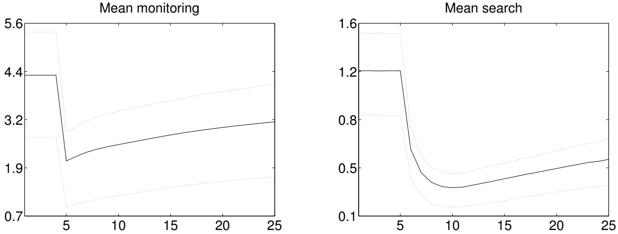


Figure : Amplification mechanism due to feedback between monitoring and search

Monetary Policy Analysis: Changes in Interest Rate Corridor

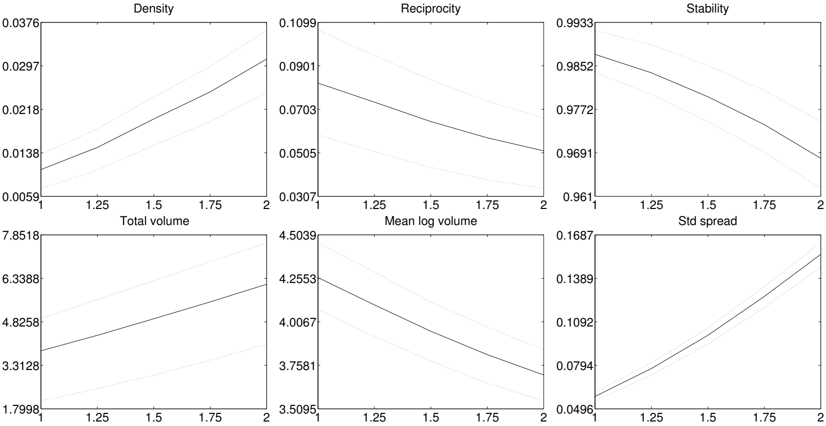
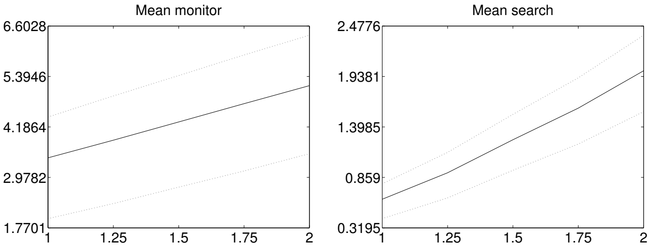


Figure : Responses of lending network structure

Monetary Policy Analysis: The Multiplier Effect of Monitoring



Changes in lending network are driven by **two effects**

- **Direct effect** on interbank lending activity by altering outside options
- **Indirect multiplier effect** through changes in monitoring and search efforts

Conclusion

- We introduce and **estimate structural interbank network model** where banks monitor and search counterparties for bilateral bargaining in OTC market
- CR uncertainty and monitoring are key driver of **sparse core-periphery structure** trading network and existence of **relationship lending**
- **Dynamic analysis** reveals importance of monitoring and search as driver behind prolonged market inactivity after shock to uncertainty
- **Changes in discount window** lead to direct effect on interbank lending and indirect multiplier effect through altered monitoring and search efforts

A Dynamic Network Model of the Unsecured Interbank Lending Market[1]

Francisco Blasques[a] Falk Bräuning[b] Iman van Lelyveld[a,c]

[a]VU University Amsterdam
[b]Federal Reserve Bank of Boston
[c]De Nederlandsche Bank

The Role of Liquidity in the Financial System
Atlanta, November 19th, 2015

[1]The views expressed in this presentation do not necessarily represent those of the Federal Reserve Bank of Boston, the Federal Reserve System, De Nederlandsche Bank, or the Eurosystem.

Details of Bilateral Interest Rate Bargaining

- For bank i, lending funds to bank j at time t is a risky investment

$$R_{i,j,t} = \begin{cases} r_{ijt} & \text{w.p. } 1 - P_{i,j,t} \\ -1 & \text{w.p. } P_{i,j,t}. \end{cases}$$

with expected return (expectation under perceived probability measure)

$$\bar{R}_{i,j,t} = \mathbb{E}_t R_{i,j,t} = (1 - P_{i,j,t}) r_{i,j,t} - P_{i,j,t}.$$

- For borrowing bank j cost of borrowing are simply $r_{i,j,t}$
- Bilateral Nash bargaining solution then satisfies

$$r_{i,j,t} \in \arg\max_{r} \left((1 - P_{i,j,t}) r - P_{i,j,t} - \underline{r}\right)^{\theta} \left(\overline{r} - r\right)^{1-\theta}.$$

- Back to Bargaining

Details of Indirect Inference Estimation

- We use quadratic form with diagonal weight matrix (equal unit weights, except density and RL measures which are set to 10 and 50), $S = 24$ simulated networks with each $T^* = 3000$, burning 1000 periods

- The reduced form can be written as a nonlinear Markov autoregressive process,

$$\mathbf{X}_t = \mathbf{G}_{\boldsymbol{\theta}}(\mathbf{X}_{t-1}, \mathbf{e}_t)$$

- Restrict parameter space Θ to ensure model identification and stability; contraction condition to ensure stability of dynamic network

$$\mathbb{E} \log \sup_{\mathbf{x}} \|\nabla \mathbf{G}_{\boldsymbol{\theta}}(\mathbf{x}, \mathbf{e}_t)\| < 0$$

where $\nabla \mathbf{G}_{\boldsymbol{\theta}}$ denotes the Jacobian of $\mathbf{G}_{\boldsymbol{\theta}}$ and $\|\cdot\|$ is a norm.

- Lyapunov stability of the dynamic stochastic network model

Parameter vector	initial point: $\boldsymbol{\theta}_0$	estimated point: $\hat{\boldsymbol{\theta}}_T$
Lyapunov exponent	-0.6451	-0.2462

- Back to Estimation

Details of Auxiliary Statistics

Table : Auxiliary network statistics. The table reports the values of the observed auxiliary statistics $\hat{\boldsymbol{\beta}}_T$ used in the indirect inference estimation along with the HAC robust standard errors. The simulated average of the auxiliary statistics $\tilde{\boldsymbol{\beta}}_{TS}$ for $S = 24$ paths is shown for the estimated parameter vector $\hat{\boldsymbol{\theta}}_T$ and the alternative calibration $\boldsymbol{\theta}_a$ (model without monitoring). The observed statistics are computed on a sample of daily frequency from 18 February 2008 to 28 April 2011 of size $T = 810$.

Auxiliary statistic	Simulated Calibrated $\tilde{\boldsymbol{\beta}}_{TS}(\boldsymbol{\theta}_a)$	Simulated Estimated $\tilde{\boldsymbol{\beta}}_{TS}(\hat{\boldsymbol{\theta}}_T)$	Observed $\hat{\boldsymbol{\beta}}_T$	Observed ste$(\hat{\boldsymbol{\beta}}_T)$
Density (mean)[a]	0.1121	0.0193	0.0212	0.0026
Reciprocity (mean)	0.0453	0.0627	0.0819	0.0029
Stability (mean)	0.8247	0.9795	0.9818	0.0025
Avg clustering (mean)	0.1097	0.0347	0.0308	0.0027
Avg degree (mean)	5.4948	0.9441	1.0380	0.1291
Std outdegree (mean)	3.2901	1.6547	1.8406	0.0918
Skew outdegree (mean)	0.4512	2.3649	2.8821	0.3537
Std indegree (mean)	4.7450	1.6950	1.6001	0.0995
Skew indegree (mean)	0.3300	2.2801	2.4030	0.3143
Corr$(r_{i,j,t}, l^{rw}_{i,j,t-1})$ (mean)	0.0000	-0.1231	-0.0716	0.0113
Corr$(l_{i,j,t}, l^{rw}_{i,j,t-1})$ (mean)	0.2345	0.6001	0.6439	0.0107
Avg log volume (mean)	2.8298	3.9422	4.1173	0.0516
Std log volume (mean)	1.0547	1.0865	1.6896	0.0200
Skew log volume (mean)	-0.1187	-0.1357	-0.3563	0.0317
Avg interest rates (mean)	1.0348	1.1353	0.2860	0.1331
Std interest rates (mean)	0.0000	0.1004	0.1066	0.0142
Skew interest rates (mean)	0.0251	1.6010	0.6978	0.5295
Corr(density,stability)	-0.4688	-0.3837	-0.7981	0.0275
Corr(density,rates)	0.0296	0.0896	0.7960	0.0229
Autocorr(density)	0.0034	0.2455	0.8174	0.0243
Autocorr(avg volume)	0.0014	0.0760	0.4926	0.0555
Autocorr(avg rate)	0.9991	0.2425	0.9655	0.0031
Objective function value	227.3328	4.2407		
Euclidean norm $\Vert\hat{\boldsymbol{\beta}}_T - \tilde{\boldsymbol{\beta}}_{TS}\Vert$	6.8563	2.0035		
Sup norm $\Vert\hat{\boldsymbol{\beta}}_T - \tilde{\boldsymbol{\beta}}_{TS}\Vert_\infty$	4.4568	0.9032		

[a] Not included in vector of auxiliary statistics as proportional to average degree.

Back to Auxiliary Statistics

Details of Parameter Estimates

Table : Estimated parameter values. The table reports the estimated structural parameters ($\hat{\boldsymbol{\theta}}_T$) and corresponding standard errors and 90% confidence bounds. The parameter $\boldsymbol{\theta}_a$ represents an calibrated model parametrization without monitoring ($\beta_{\phi,1} = 0$). For calibrated parameters no standard errors and confidence bounds are reported. The indirect inference estimator is based on $S = 24$ simulated network sequences of length $T^* = 3000$. Note also that $\sigma^*_\mu = \log(\sigma_\mu)$.

Structural parameters		Calibrated $\boldsymbol{\theta}_a$	Estimated $\hat{\boldsymbol{\theta}}_T$	St.Errors ste($\hat{\boldsymbol{\theta}}_T$)	90% Bounds LB	UB
Added information	α_ϕ	-1.5000	-1.5000	-	-	-
	$\beta_{\phi,1}$	0.0000	9.6631	0.0006	9.6619	9.6643
	$\beta_{\phi,2}$	0.0001	0.0001	0.0445	-0.0871	0.0873
Perception error variance	α_σ	1.2890	1.2890	0.0028	1.2835	1.2945
	β_σ	-2.0000	-2.0000	-	-	-
	γ_σ	0.6648	0.6648	0.0183	0.6289	0.7007
	δ_σ	0.3383	0.3383	0.0451	0.2499	0.4267
Search technology	α_λ	0.0001	0.0001	0.1159	-0.2271	0.2273
	β_λ	72.8331	72.8331	0.0006	72.8319	72.8343
Liquidity shocks	μ_μ	0.0000	0.0000	-	-	-
	σ^*_μ	1.9903	1.9903	0.0228	1.9456	2.0350
	μ_σ	1.9492	1.9492	0.0218	1.9065	1.9919
	σ_σ	1.9810	1.9810	0.0213	1.9393	2.0227
	ρ_ζ	-0.7826	-0.7826	0.0423	-0.6997	-0.8655
Expectations	λ^y	0.8472	0.8472	0.0443	0.7604	0.9340
	λ^B	0.9278	0.9278	0.0470	0.8357	1.0199
	λ^r	0.4008	0.4008	0.0466	0.3095	0.4921
	$\lambda^{\tilde{\sigma}}$	0.0318	0.0318	0.0414	-0.0493	0.1129
Bargaining lender	θ	0.6897	0.6896	0.0441	0.6032	0.7760
CB corridor width	r	1.5000	1.5000	-	-	-
Default threshold	ϵ	3.0000	3.0000	-	-	-
Financial distress	σ	0.1000	0.1000	-	-	-
Discount rate	r^d	1.7500	1.7500	-	-	-
Scale logistic	β_l	200.00	200.00	-	-	-

Back to Parameter Estimates