Contagion Effect in Financial Networks: Sustainability and Optimal Number of Banks

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June 27, 2024

Introduction

Financial Network

is a collection of interbank obligations (deposits).

Contagion Effect

is a propagation of one financial institution's problems to others.

Sustainability of Network Architecture

RQ 1: Which systems are more or less resistant to contagion?

Complete

- Allen and Gale (2000b)
- Hasman and Samartin (2008)

Ring

- Acemoglu et al. (2012, 2013)
- Brusco and Castiglionesi (2005)

Intermediate view: Acemoglu et al. (2015); Castiglionesi et al. (2019) + Haldane (2009)

Empiric: Belgium case (Degryse and Nguyen, 2004)

Optimal Network Saturation

RQ 2: Is it possible to find the optimal number of banks to increase network stability?

1. **Theory:**
   - Bertrand competition under asymmetric information (Dell'ariccia et al., 1999): two banks in equilibrium.
   - Optimal Bank Size: (Cerasi and Daltung, 2000; Villamil and Krasa, 1992; Broll and Wahl, 2002; Miles et al., 2012; Estrella, 2004)

2. **Empiric:**
   - Optimal number: Pagano et al. (2014)
   - Optimal size: Vallascas and Keasey (2012)

Optimal Deposit Distribution

RQ 3: How does the distribution of deposits among banks affect the stability of the system?

The banking literature has not reached a consensus on how market concentration affects financial stability (Allen and Gale, 2004; Carletti and Hartmann, 2003).

Competition-fragility

- Hellmann et al. (2000)
- Allen and Gale (2000a)
- Keeley (1990)

Competition-stability

- Fiordelisi and Mare (2014)
- Tabak et al. (2013)

Policy of the Monetary Regulator

RQ 4: What are the consequences of the monetary regulator's policy?

Main Points

Literature Gaps:

1. There is an ambiguity which of the systems is more stable: a ring or a complete.
2. There is no model for finding the optimal number of banks to reduce the consequences of contagion.
3. There is no clear opinion on how capital should be distributed among banks.

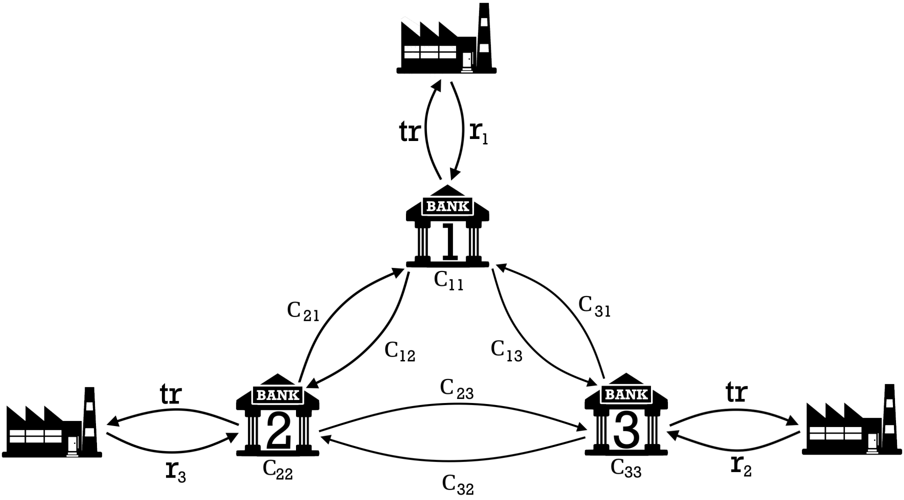
Methodology: Simulations on **Python**.

Novelty:

1. Non-standard metrics of analysis.
2. Introduction of the interbank panic into the model.

Model Setup

Economy Scheme



System Types to Consider

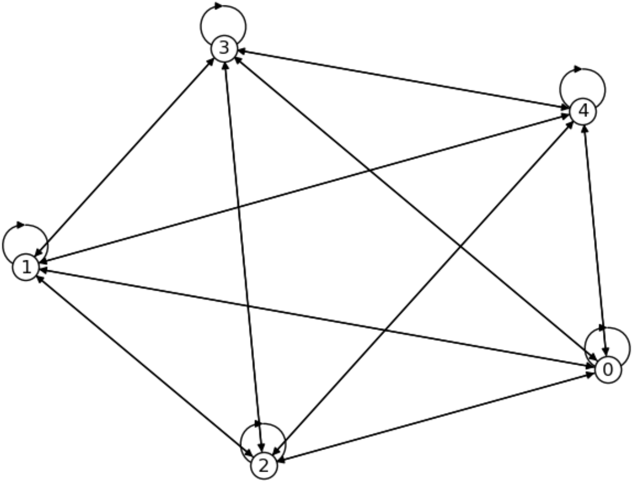
As in the literature:

- complete
- ring

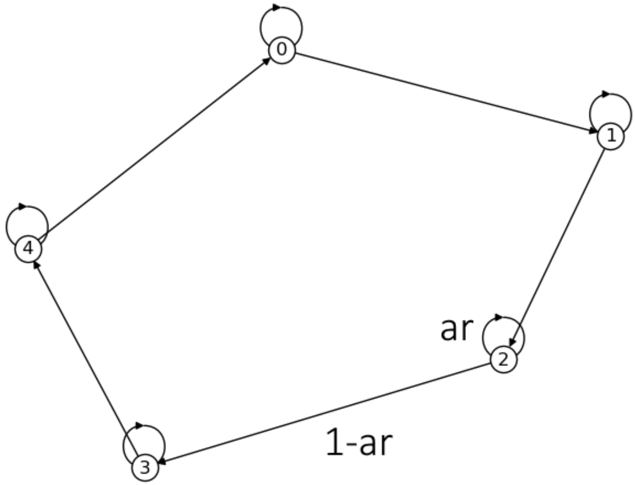
Additional:

- star
- n-connected ($n = f(N) = round(\sqrt{N})$)

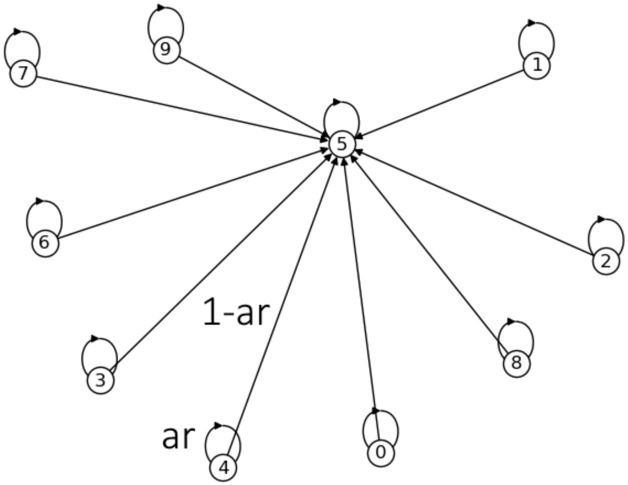
System types: complete



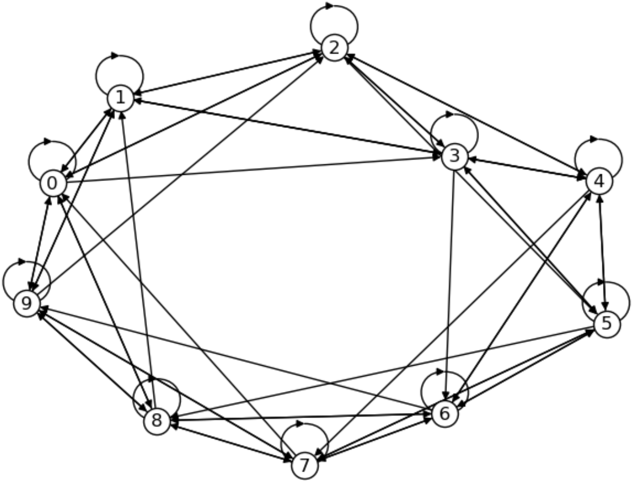
System types: ring



System types: star



System types: n-connected (//2, ln, **sqrt**, ...)



Claims Matrix

$$Claims = \begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ c_{N1} & c_{N2} & \cdots & c_{NN} \end{pmatrix}$$

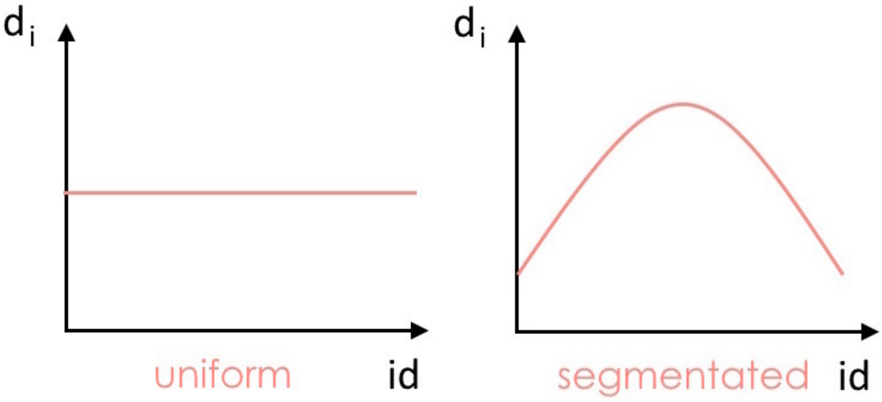
c_{ii} - reserves of Bank i,
c_{ij} - total deposits of Bank i in Bank j and, at the same time, debt of Bank j to Bank i.

Deposit Distribution Effect

Types:

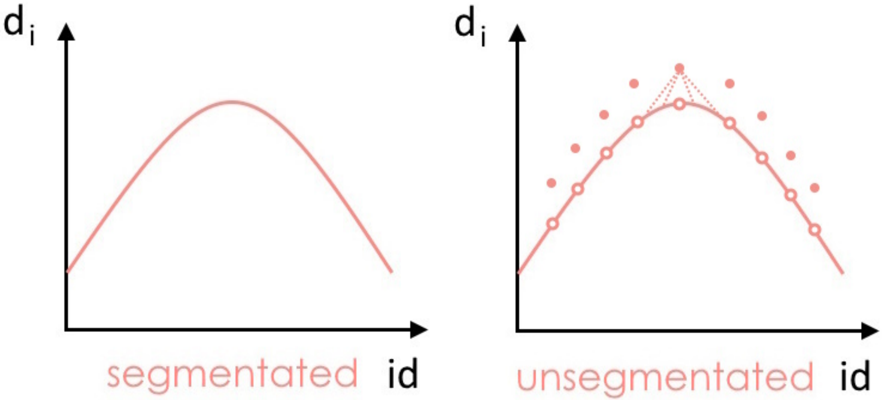
1. Uniform: $D(i) = 1$
2. Segmentated: $D(i) = sin\left(2\pi\left(\frac{i}{N+1} - 0.25\right)\right) + 2$
3. Unsegmentated: Within a unsegmented distribution, large banks are selected from the segmented one and are evenly redistributed along the n-connected ring so that among the partners of large banks there are only small ones.
   It is unsegmented in the sense that large banks do not separate from small ones, but, on the contrary, invest only in them.

Deposit Distribution Effect: Heterogeneity



Deposit Distribution Effect: Segmentation

Compares only for n-connected system

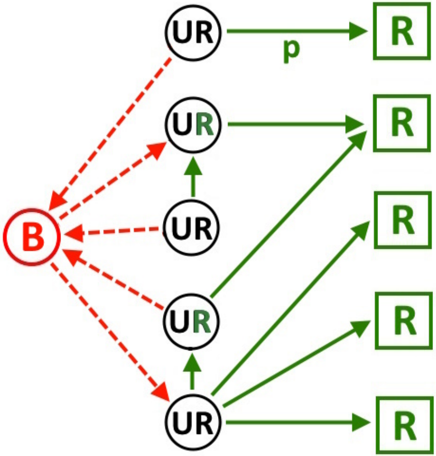


Methodology of Contagion

In Espinosa-Vega and Sole (2011) two types of shocks (for bank i if bank z fall) are considered:

- credit: $\lambda_c \cdot c_{iz}$
- founding: $\lambda_f \cdot c_{zi}$

Interbank Panic Scheme



B – bankrupt bank, UR – under run banks, R – runners, p – rate of withdrawal.

Methodology of Contagion: Stress Testing

Timing:

1. bank i is declared bankrupt
2. banks-depositors of the bankrupt's partners raid them and withdraw some of the deposits
3. bankrupt's partners experience financial losses (credit shock and funding shock)
4. assessing which banks went bankrupt
5. then this algorithm is repeated (now the input is not just one initial bankrupt bank but all new ones)

Simulations

In line with Espinosa-Vega and Sole (2011), following metrics are used:

- Money* Reduction
- Triggered Bankruptcies
- Index and Level Vulnerability

Optimal number and sustainability – four regimes to consider:

- Financial Collapse
- No Panic
- Panic
- Regulator's Policy

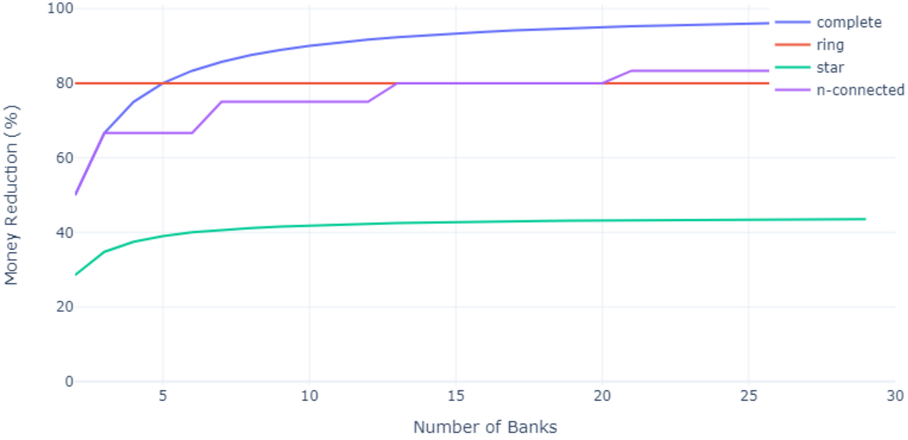
Simulation Outcomes

Financial Collapse

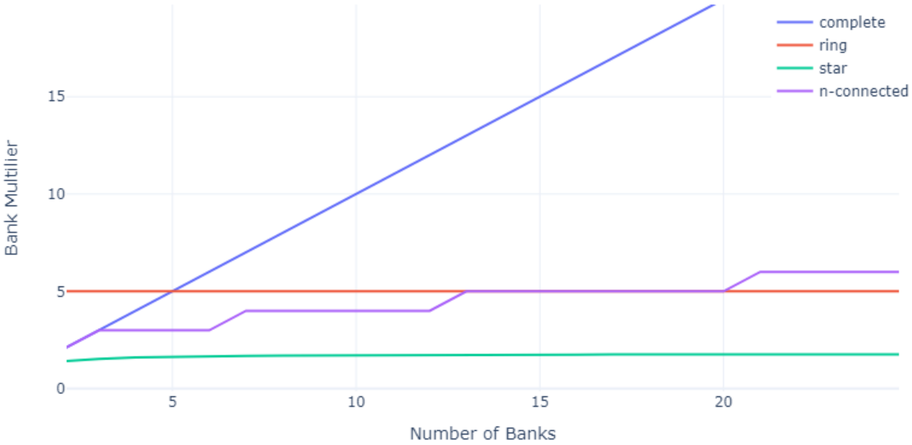
Definition

Financial collapse is the bankruptcy of all banks in the banking system.

Systems Sustainability



Systems Sustainability



Systems Sustainability

	$bm(N)$	$mr(N)$	mr_∞
complete	N	$1-\frac{1}{N}$	1
ring	$\frac{1}{ar}$	$1-ar$	$1-ar$
n-connected	$n=f(N)=round(\sqrt{N})$	$1-\frac{1}{round(\sqrt{N})+1}$	1
star	$1+\frac{N-1}{N}(1-ar)$	$1-\frac{1}{2-ar-\frac{1-ar}{N}}$	$1-\frac{1}{2-ar}$

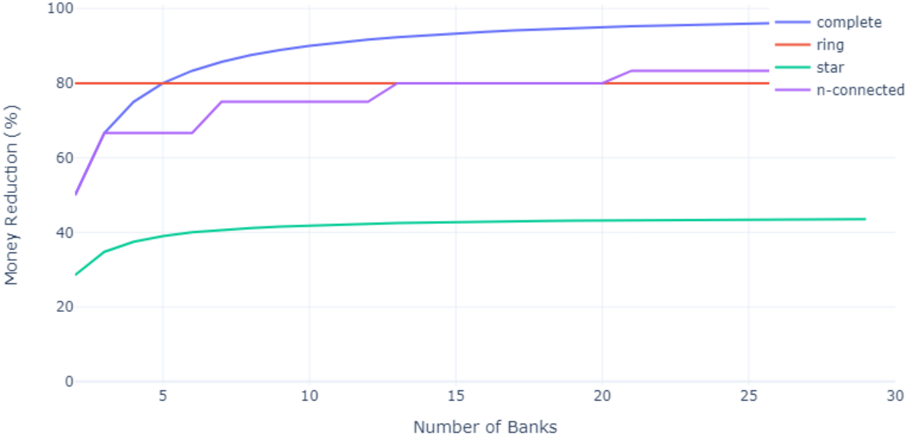
System ranking by stability: star $\succ$ n-connected $\succeq$ complete, star $\succeq$ ring. But the ring can be more or less stable than the complete and n-connected structures.

Systems Sustainability

Robust-efficiency trade-off

Either the financial system is very stable and then it (almost) does not meet financial needs of the economy, or it is high interconnected structure that effectively create money but then it becomes vulnerable to contagion.

Optimal Network Saturation



No Panic Regime

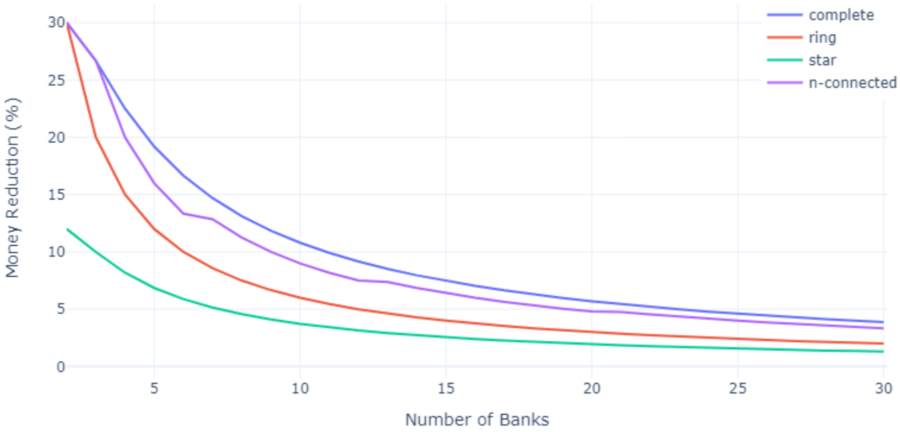
Definition

Small shock is a bankruptcy of initial bank that will not cause any of its partners to go bankrupt.

Definition

Large shock is a bankruptcy of initial bank that will cause at least one of its partners to go bankrupt.

Systems Sustainability: Small Shock



Systems Sustainability: Small Shock

	$mr(N)$	mr_∞
complete	$\frac{(N-1)(2-\lambda_c-\lambda_f)}{N^2}$	0
ring	$\frac{1-ar}{N}(2-\lambda_c-\lambda_f)$	0
n-connected	$\frac{n(2-\lambda_c-\lambda_f)}{N(n+1)}$	0
star	$\frac{(N-1)(1-ar)(2-\lambda_f-\lambda_c)}{N^2+(1-ar)(N^2-N)}$	0

System ranking by stability: star $\succeq$ n-connected $\succeq$ complete, star $\succeq$ ring.

Optimal Network Saturation: Small Shock

	$mr(N)$	mr_∞
complete	$\frac{(N-1)(2-\lambda_c-\lambda_f)}{N^2}$	0
ring	$\frac{1-ar}{N}(2-\lambda_c-\lambda_f)$	0
n-connected	$\frac{n(2-\lambda_c-\lambda_f)}{N(n+1)}$	0
star	$\frac{(N-1)(1-ar)(2-\lambda_f-\lambda_c)}{N^2+(1-ar)(N^2-N)}$	0

Functions are not strictly monotonic, the optimum is boundary (∞), not inner.

Deposit Distribution: n-connected

Deposit Distribution

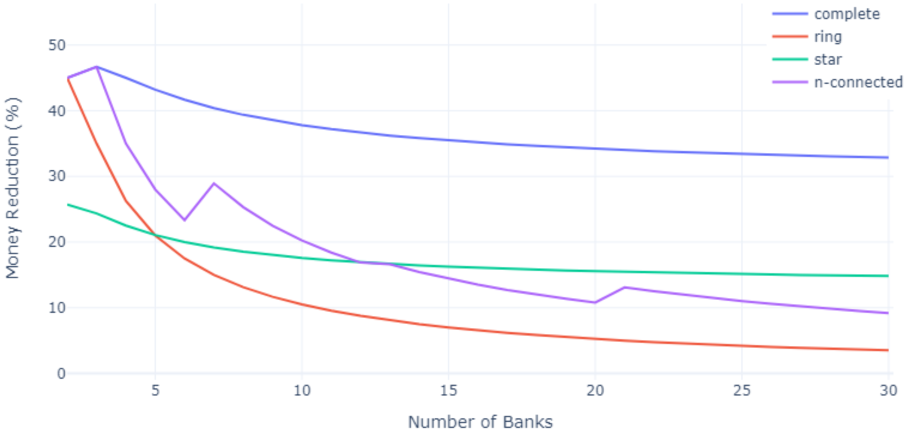
'Robust-yet-fragile' concept Haldane (2009) revisited:

Heterogeneity buffer

The heterogeneity of banks in terms of deposits allows the system to have a partial bankruptcy rate, rather than 0 or 100%. This increases the stability of the system under large shocks.

Panic Regime

Systems Sustainability: Small Shock



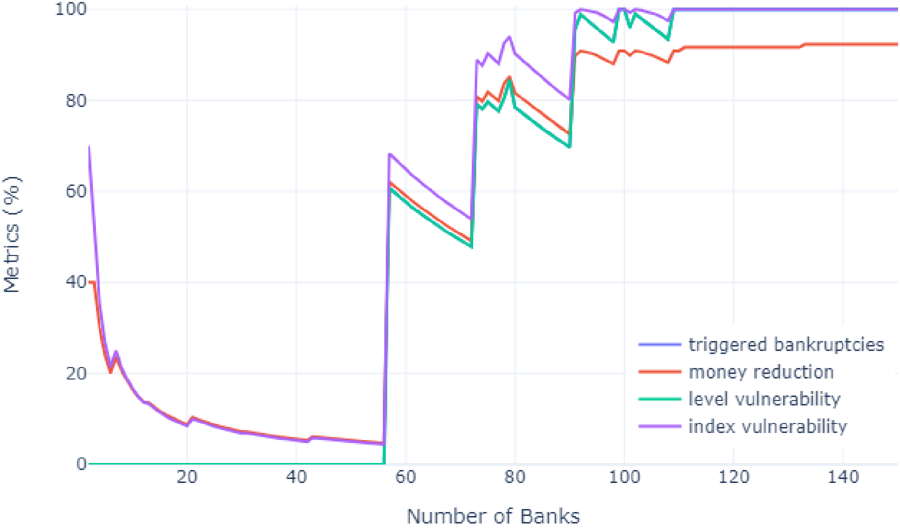
Systems Sustainability: Small Shock

	$mr(N)$	mr_∞
complete	$\frac{p(N^2-3N+2)+(N-1)(2-\lambda_c-\lambda_f)}{N^2}$	p
ring	$\frac{1-ar}{N}(p+2-\lambda_c-\lambda_f)$	0
n-connected	$\frac{n(2+pn-\lambda_c-\lambda_f)}{N(n+1)}$	0
star	$\frac{(N-1)(1-ar)(2-\lambda_f-\lambda_c+p(N-2))}{N^2+(1-ar)(N^2-N)}$	$\frac{(1-ar)p}{2-ar}$

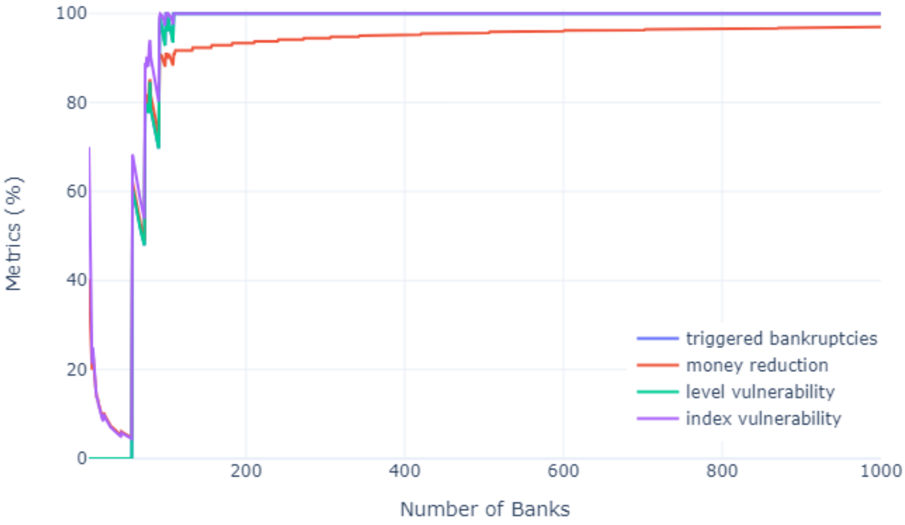
If $N=2$: $p=0$.

Ranking depends on the parameters: $N, p, \lambda_c, \lambda_f, ar$.

Optimal Network Saturation: n-connected

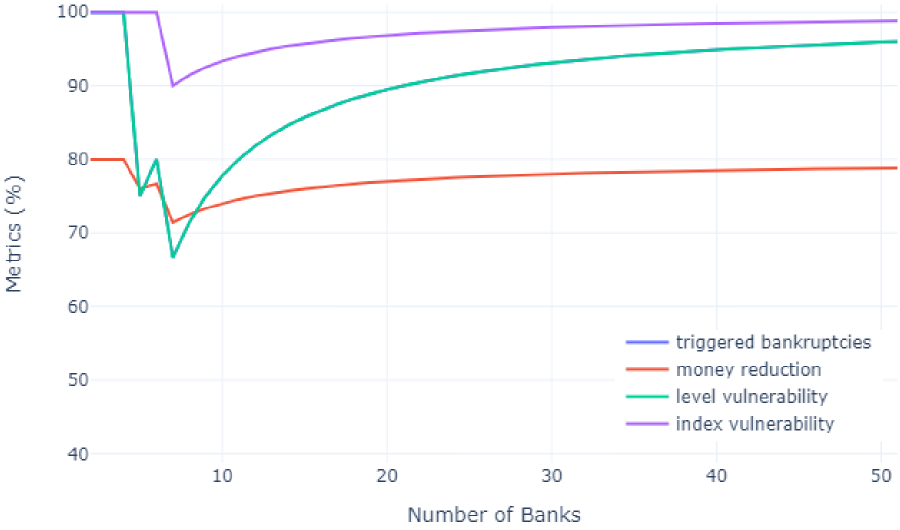


Optimal Network Saturation: n-connected

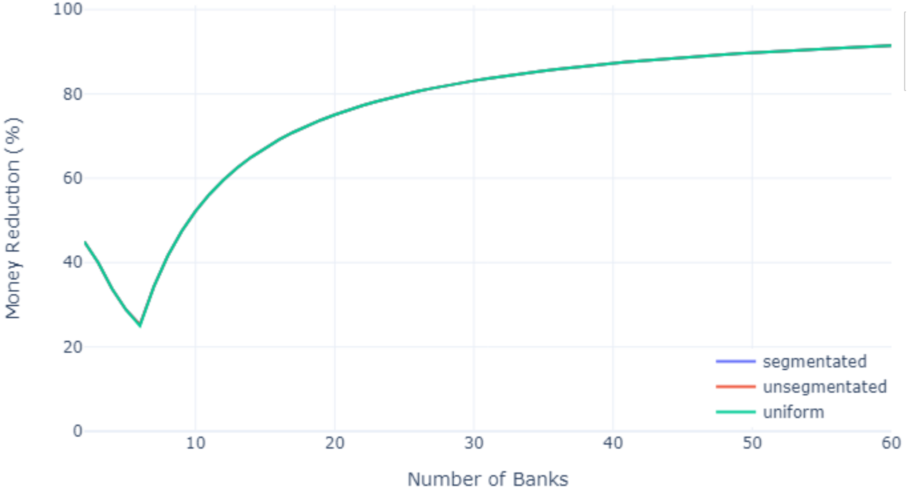


Optimal Network Saturation: n-connected

Optimal Network Saturation: ring



Optimal Network Saturation: complete



Optimal Network Saturation: complete

We can derive expression for this optimal number of banks in case of uniform distribution:

$N^* = \lceil \frac{1}{\lambda_c + \lambda_f} + 1 \rceil$, $\lceil \dots \rceil$ stands for rounding up.

Deposit Distribution

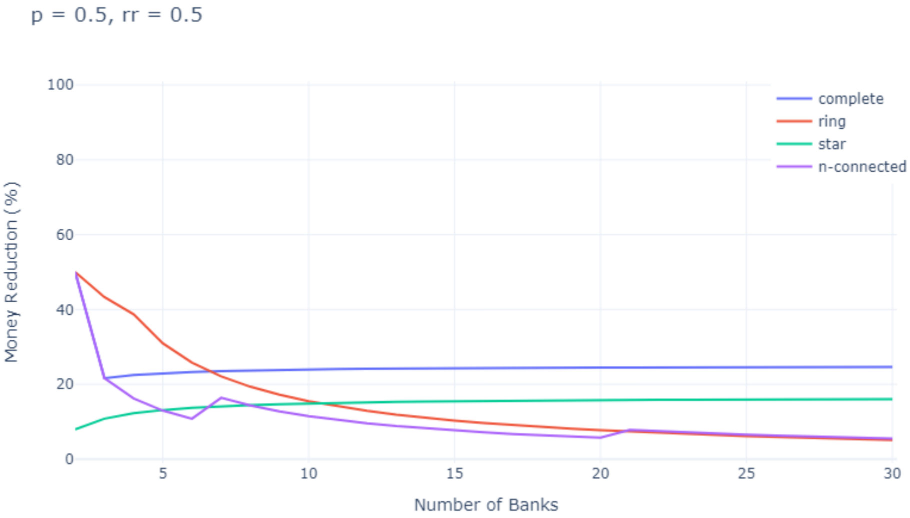
Regulator's Policy

Policy Menu

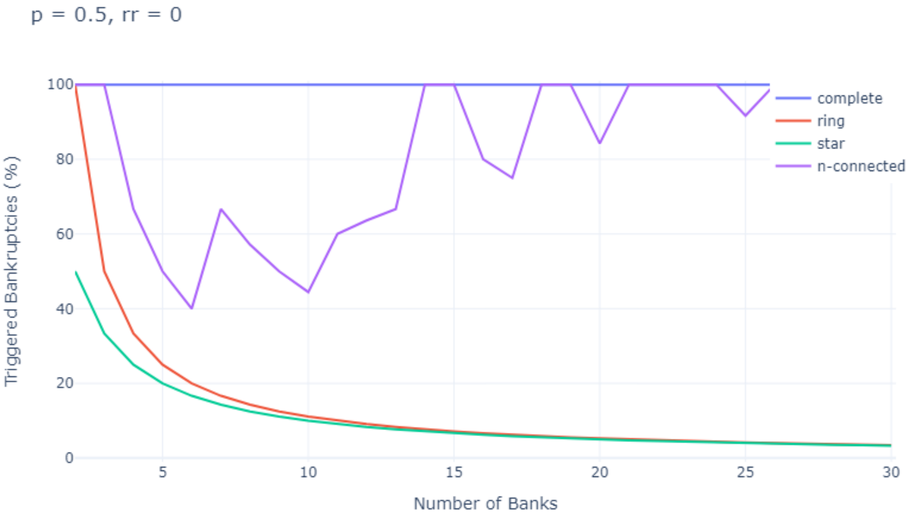
is presented in the form of assigning a reserve requirement for banks, rr.

Policy Results

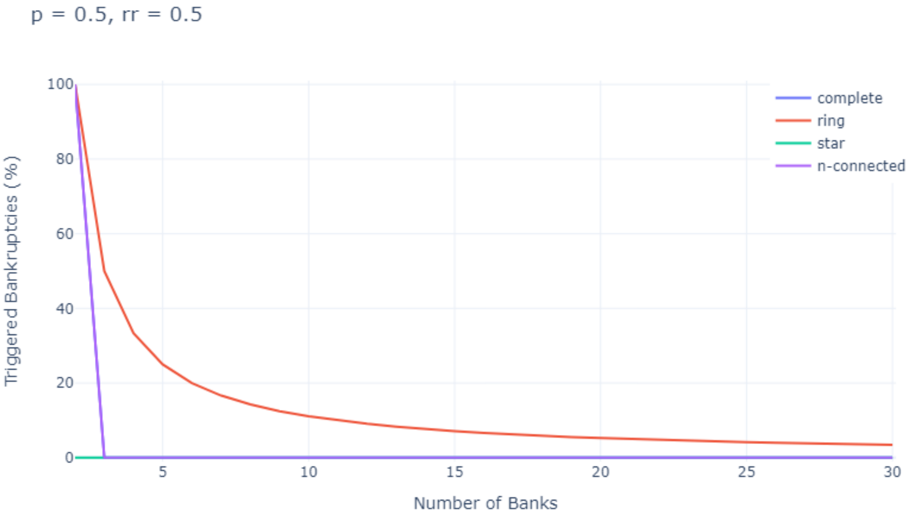
Policy Results



Policy Results



Policy Results



Side Effects of Regulation

Initial deposits vector $= (82, 19, 33, 4)$. Two cases: $rr = 0$ and $rr = 0.2$.

$$B_0 = \begin{pmatrix} 0.14 & 0.66 & 0.14 & 0.06 \\ 0.13 & 0.06 & 0.75 & 0.06 \\ 0.4 & 0.36 & 0.14 & 0.1 \\ 0.01 & 0.3 & 0.3 & 0.39 \end{pmatrix} \quad B_{rr} = \begin{pmatrix} 0.2 & 0.66 & 0.14 & 0 \\ 0.11 & 0.2 & 0.69 & 0 \\ 0.37 & 0.33 & 0.2 & 0.1 \\ 0.01 & 0.3 & 0.3 & 0.39 \end{pmatrix}$$

Rounded claims matrix:

$$C_0 = \begin{pmatrix} 38 & 178 & 38 & 16 \\ 45 & 21 & 261 & 21 \\ 142 & 128 & 50 & 35 \\ 1 & 23 & 23 & 30 \end{pmatrix}$$

Rounded claims matrix:

$$C_{rr} = \begin{pmatrix} 38 & 125 & 27 & 0 \\ 25 & 45 & 156 & 0 \\ 83 & 74 & 45 & 22 \\ 0 & 8 & 8 & 10 \end{pmatrix}$$

Side Effects of Regulation

Rounded dependency matrix:

$$DM_0 = \begin{pmatrix} 0 & 5.9 & 4.8 & 0.5 \\ 10.7 & 0 & 18.6 & 2.1 \\ 3.6 & 7.8 & 0 & 1.2 \\ 0.6 & 1.5 & 2 & 0 \end{pmatrix} \quad DM_{rr} = \begin{pmatrix} 0 & 4 & 2.9 & 0 \\ 3.3 & 0 & 5 & 0.2 \\ 2.4 & 5.1 & 0 & 0.7 \\ 0 & 0.8 & 2.9 & 0 \end{pmatrix}$$

The dependency matrix is obtained based on the claims matrix:
$DM_{ij} = (C_{ij} + C_{ji})/C_{ii}$.

Summary

1. Systems can be ordered in terms of stability, however, for a ring system, its relative position changes depending on the reservation rate.
2. An internal optimum exists in the complete, ring and n-connected systems, but only if there is a panic in the interbank market. Moreover, optima exist even with the endogenized version of panic.
3. large banks should not be separated from small ones and interact with them. In the case of large shock in the absence of panic, evenness in the distribution of deposits has a negative effect on stability.
4. An increase reserve requirements by CB, while generally increasing the stability of the financial system, may make some banks more vulnerable to a contagion.

Extra Slides

Origins of Contagion

- Financial linkages between agents (Rochet and Tirole, 1996; Allen and Gale, 2000b; Hasman and Samartin, 2008; Aghion et al., 2000; Freixas et al., 2000; Acemoglu et al., 2012, 2013, 2015; Brusco and Castiglionesi, 2005)
- Bank panic (Diamond and Dybvig, 1983; Jacklin and Bhattacharya, 1988)
- Restrictions on wealth (Kyle and Xiong, 2001)
- Liquidity constrains (Kodres and Pritsker, 2002)
- Features of the financial intermediary incentive system (Schinasi and Smith, 2000)
- Chain devaluation of assets between countries (Pericoli and Sbracia, 2003)

Transmission Matrix

$$B = \begin{pmatrix} \beta_{11} & \beta_{12} & \dots & \beta_{1N} \\ \beta_{21} & \beta_{22} & \dots & \beta_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{N1} & \beta_{N2} & \dots & \beta_{NN} \end{pmatrix}$$

β_{ii} - the share which Bank i keeps in own reserves
β_{ij} - the share which Bank i invests from the received funds in Bank j

Model Setup

$$\begin{cases} b^1_{t+1} = \beta_{21} b^2_t + \beta_{31} b^3_t + \ldots + \beta_{N1} b^N_t \\ b^2_{t+1} = \beta_{12} b^1_t + \beta_{32} b^3_t + \ldots + \beta_{N2} b^N_t \\ b^3_{t+1} = \beta_{13} b^1_t + \beta_{23} b^2_t + \ldots + \beta_{N3} b^N_t \\ \ldots \\ b^N_{t+1} = \beta_{1N} b^1_t + \ldots + \beta_{N-1,N} b^{N-1}_t \end{cases}$$

with vector of initial deposits $\mathrm{b}_0 = (d_1, d_2, \ldots, d_N)^T$

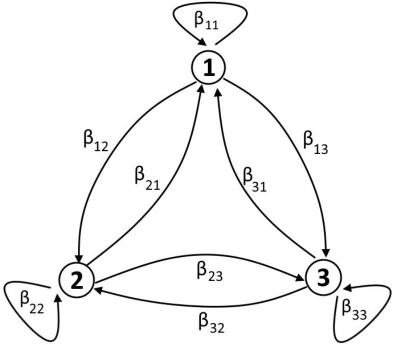


Figure: Weighted graph for 3-banks system

Example

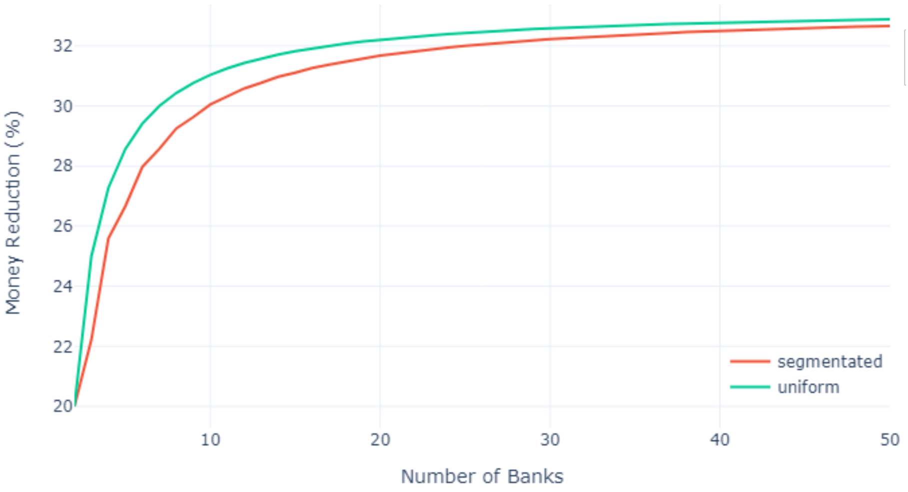
Example of a transmission matrix and its corresponding claims matrix:

$$B = \begin{pmatrix} 0.1 & 0.5 & 0.2 & 0.2 \\ 0.2 & 0.1 & 0.5 & 0.2 \\ 0.2 & 0.2 & 0.1 & 0.5 \\ 0.5 & 0.2 & 0.2 & 0.1 \end{pmatrix}$$

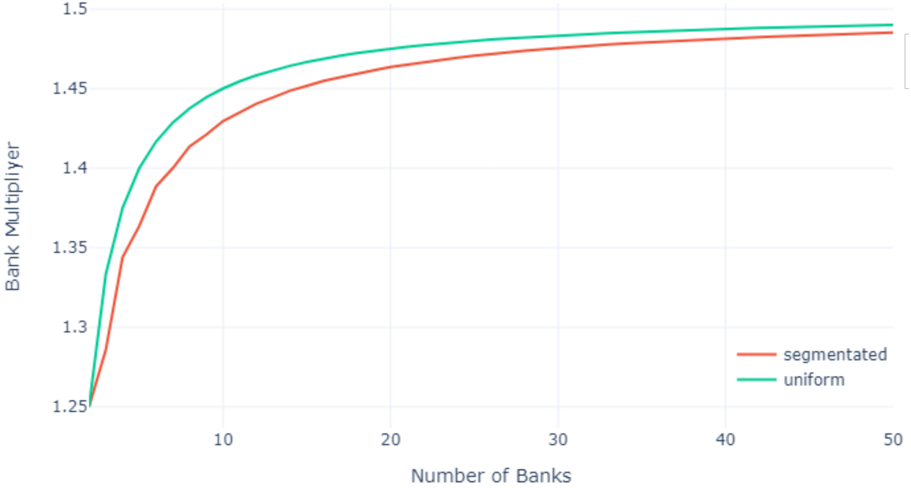
initial deposits vector $b_0 = (20, 30, 15, 10)$

$$Claims(rounded) = \begin{pmatrix} 19 & 93 & 37 & 37 \\ 39 & 20 & 98 & 39 \\ 37 & 37 & 19 & 93 \\ 90 & 36 & 36 & 18 \end{pmatrix}$$

Deposit Distribution: Star



Deposit Distribution: Star



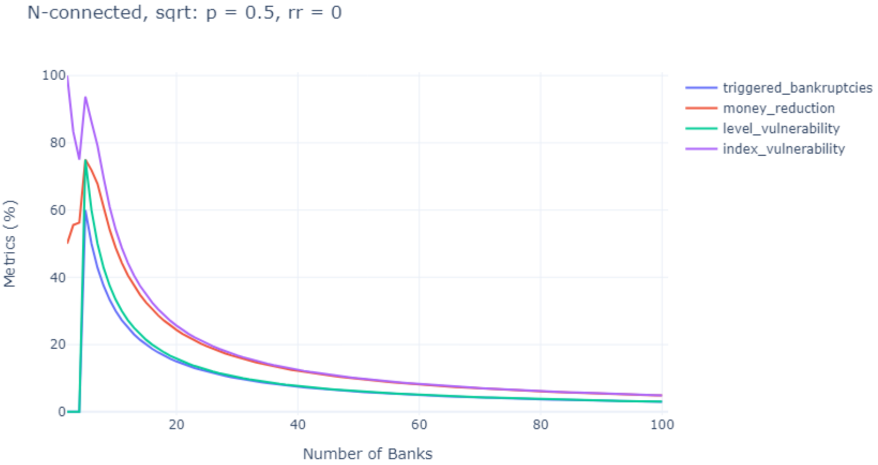
Small/Large Shock

Large Shock $\rightarrow$ Financial Collapse

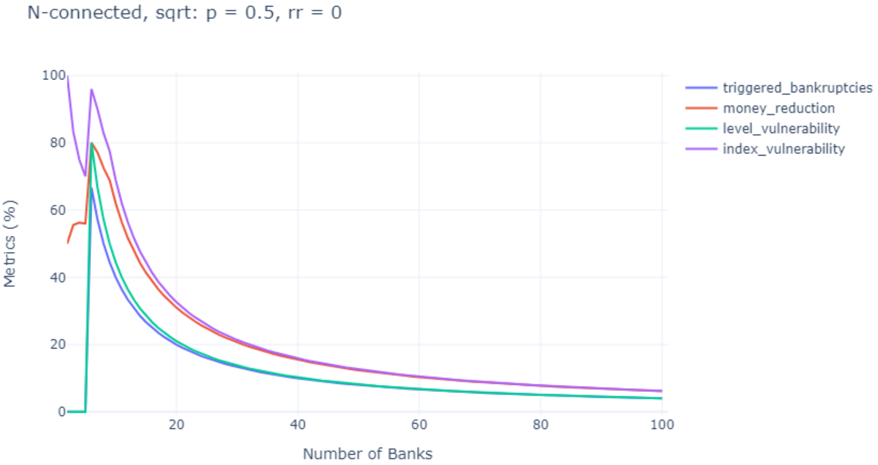
in regular systems with uniform distributions (all ones except star)

System ranking by stability: star $\succ$ n-connected $\succeq$ complete, star $\succeq$ ring.

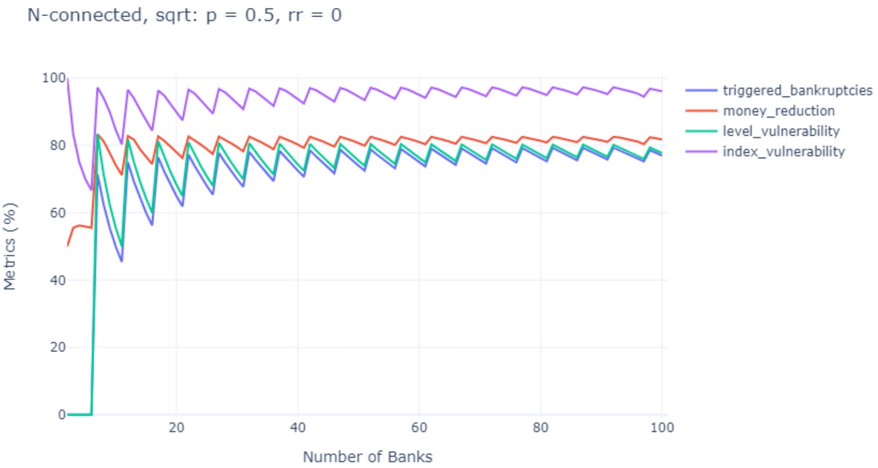
3-connected System: optimum



4-connected System: optimum



5-connected System: optimum



Summary

- **Financial Collapse**

	$bm(N)$	$mr(N)$	mr_∞
complete	N	$1-\frac{1}{N}$	1
ring	$\frac{1}{ar}$	$1-ar$	$1-ar$
n-connected	$n=f(N)=round(\sqrt{N})$	$1-\frac{1}{round(\sqrt{N})+1}$	1
star	$1+\frac{N-1}{N}(1-ar)$	$1-\frac{1}{2-ar-\frac{1-ar}{N}}$	$1-\frac{1}{2-ar}$

System ranking by stability: star $\succ$ n-connected $\succeq$ complete, star $\succeq$ ring. The ring structure, although always less stable than the star, can be more or less stable than the complete and n-connected structures under some N.

Summary

For a ring structure, any number of banks is optimal in terms of money reduction, and for all other structures: the smallest possible number is the best (namely, 2).

Deposit distributions ranking by stability can only be found for a star: segmentated $\succeq$ uniform. For other systems, all distributions are equivalent in terms of the metrics under study.

Summary

- **No Panic Regime, Small Shock**

	$mr(N)$	mr_∞
complete	$\frac{(N-1)(2-\lambda_c-\lambda_f)}{N^2}$	0
ring	$\frac{1-ar}{N}(2-\lambda_c-\lambda_f)$	0
n-connected	$\frac{n(2-\lambda_c-\lambda_f)}{N(n+1)}$	0
star	$\frac{(N-1)(1-ar)(2-\lambda_f-\lambda_c)}{N^2+(1-ar)(N^2-N)}$	0

System ranking by stability: star $\succeq$ n-connected $\succeq$ complete, star $\succeq$ ring. The ring structure, although at least not more stable than star, can be more or less stable than the complete and n-connected structures under some N.

Summary

The optimum in the number of banks is boundary — infinity.

Deposit distributions ranking by stability: depends on how you aggregate bank stress testing data.

Summary

- **No Panic Regime, Large shock**
  In regular systems with an even distribution of deposits, if there is at least one induced bankruptcy, then financial collapse occurs. The only irregular system is the star, but it remains the most stable regardless of the parameters. So, star $\succeq$ n-connected $\succeq$ complete and star $\succeq$ ring.

  With a large shock, two possible optimal number of banks: two and infinity.

  Deposit distributions ranking by stability: unsegmentated $\succeq$ segmented $\succeq$ uniform.

Summary

- **Panic Regime, Small Shock**
  The systems can be compared with each other in the money reduction metric, using the expressions below. However, the result of the comparison depends on the number of banks in the system:

	$mr(N)$	mr_∞
complete	$\frac{p(N^2-3N+2)+(N-1)(2-\lambda_c-\lambda_f)}{N^2}$	p
ring	$\frac{1-ar}{N}(p+2-\lambda_c-\lambda_f)$	0
n-connected	$\frac{n(2+pn-\lambda_c-\lambda_f)}{N(n+1)}$	0
star	$\frac{(N-1)(1-ar)(2-\lambda_f-\lambda_c+p(N-2))}{N^2+(1-ar)(N^2-N)}$	$\frac{(1-ar)p}{2-ar}$

Summary

Optimal number of banks: 2 or infinity. In the complete system, internal optimum is observed even in the case of endogenized panic.

Optimal deposit distribution: depends on the parameters.

Summary

- **Panic Regime, Large Shock**
  It is mathematically difficult to rank the systems.

  When panic is added, three types of models have an internal optimum in terms of the number of pots: complete, n-connected and ring.

  There are practically no differences between deposits distributions.

Network Adjustability

It is worth noting that the ease of network regulation was not considered in the previous literature as a criterion for possible stability.

The most unstable banking network can be made stable very easily by the presence of a central bank

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