Systemic risk in financial multilayer networks - and how to manage it

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P. Klimek, S. Poledna, J.D. Farmer, S. Thurner, To bail-out or to bail-in? Answers from an agent-based model J of Economic Dynamics and Control 50, 144-154, (2014)


M.V. Leduc, S. Poledna, S. Thurner Systemic Risk Management in Financial Networks with Credit Default Swaps 2016 (arXiv:1601.02156)


Part I: What is systemic risk?
The three types of risk

- **economic risk**: investment in business idea does not pay off
- **credit-default risk**: you don’t get back what you have lent
- **systemic risk**: system stops functioning due to local defaults and subsequent (global) cascading
Economic risk

risk that business idea does not fly — fails — investments are lost

- who takes this risk? The financial system!
- this is a service of financial system to economy
- this service should not introduce new risks: as long as it does → financial system is ill designed
- management: hard to get rid of this type of risk
Credit-default risk

if I lend something – there is risk that I will not get it back

estimate for credit-worthiness: assets–liabilities

- **management**: capital requirements for lending
  → Basle-type regulation
Systemic risk

- risk that significant fraction of financial network defaults
- systemic risk is not the same as credit-default risk
- banks care about credit-default risk
- banks have no means to manage systemic risk

→ role of regulator: manage systemic risk
→ incentivise banks to think of SR
Two origins of systemic risk

- **synchronisation of behaviour**: fire sales, margin calls, herding including various amplification effects. May involve networks

- **networks of contracts**: this is manageable
How does systemic risk spread?

SR spreads by borrowing from others!

if you borrow from systemically risky nodes
→ you increase your systemic risk

note: credit-default risk spreads by lending to
Systemic risk is a multiplex network

layer 1: lending–borrowing loans
layer 2: derivatives
layer 3: collateral
layer 4: securities
layer 5: cross-holdings
layer 6: overlapping pfolios
layer 7: liquidity: over-night loans
layer 8: FX transactions
Part II: Quantification of SR
Systemic risk – quantification

**Wanted:** systemic risk-value for every financial institution

Google has similar problem: value for importance of web-pages

→ page is important if many important pages point to it

→ number for importance → **PageRank**
page is **important** if many **important** pages point to it

source Wikipedia cc-license
Institution system. Risky if system. Risky institutions lend to it.
Systemic risk factor – DebtRank $R$

... is a “different Google” – adapted to context of systemic risk (S. Battiston et al. 2012)

superior to: eigenvector centrality, page-rank, Katz rank ...

Why?

- quantifies systemic relevance of node in financial network with economically meaningful number
- economic value in network that is affected by node’s default
- takes capitalization/leverage of banks into account
- takes cycles into account: no multiple defaults
DebtRank

- recursive method

- corrects Katz rank for loops in the exposure network

- if $i$ defaults and cannot repay loans, $j$ loses $L_{ij}$. If $j$ has not enough capital to cover that loss $\rightarrow j$ defaults

- impact of bank $i$ on neighbors $I_i = \sum_j W_{ij}v_j$

  with $W_{ij} = \min \left[1, \frac{L_{ij}}{C_j} \right]$, outstanding loans $L_i = \sum_j L_{ji}$, and $v_i = L_i / \sum_j L_j$

- impact on nodes at distance two and higher $\rightarrow$ recursive

  $$I_i = \sum_j W_{ij}v_j + \beta \sum_j W_{ij}I_j,$$
If the network $W_{ij}$ contains cycles the impact can exceed one → DebtRank (S. Battiston et al. (2012))

- nodes have two state variables, $h_i(t) \in [0, 1]$ and $s_i(t) \in \{\text{Undistress}, \text{Distress}, \text{Inactive}\}$

- Dynamics: $h_i(t) = \min\left[1, h_i(t-1) + \sum_{j|s_j(t-1)=D} W_{ji} h_j(t-1)\right]$

\[
s_i(t) = \begin{cases} 
D & \text{if } h_i(t) > 0; s_i(t-1) \neq I \\
I & \text{if } s_i(t-1) = D \\
s_i(t-1) & \text{otherwise}
\end{cases}
\]
• DebtRank of set $S_f$ (set of nodes in distress), is

$$R_S = \sum_{j} h_j(t)v_j - \sum_{j} h_j(1)v_j$$

Measures distress in the system, excluding initial distress. If $S_f$ is a single node, DebtRank measures its systemic impact on the network.

• DebtRank of $S_f$ containing only the single node $i$ is

$$R_i = \sum_{j} h_j(t)v_j - h_i(1)v_i$$
Systemic risk spreads by borrowing
Systemic risk spreads by borrowing
DebtRank Austria Sept 2009

note: size is not proportional to systemic risk
note: core-periphery structure
Systemic risk profile

Austria

![Graph showing the systemic risk profile for Austria](image)
Systemic risk profile

Mexico*

*with Serafin Martinez-Jaramillo and his team at Banco de Mexico, 2014
Daily assessment of systemic risk is possible

Mexico

TIME

SYST. RISK ALL BANKS

(b) combined
Systemic risk → expected systemic loss

**Expected loss** for bank $i$ (stress testing)

\[
\text{Expected loss}(i) = \sum_j p_{\text{default}}(j) \cdot \text{Loss-given-default}(j) \cdot \text{Exposure}(i,j)
\]

**Expected systemic loss** = \[ \sum_i p_{\text{default}}(i) \cdot \text{DebtRank}(i) \]

units: Euro / Year
\[ \text{EL}^{\text{syst}} = V \sum_{S \in \mathcal{P}(B)} \prod_{i \in S} p_i \prod_{j \in B \setminus S} (1 - p_j) (R_S) \]

\[ \approx V \sum_{S \in \mathcal{P}(B)} \prod_{i \in S} p_i \prod_{j \in B \setminus S} (1 - p_j) \left( \sum_{i \in S} R_i \right) \]

\[ = V \sum_{i=1}^{b} \left( \sum_{J \in \mathcal{P}(B \setminus \{i\})} \prod_{j \in J} p_j \prod_{k \in B \setminus (J \cup \{i\})} (1 - p_k) \right) p_i R_i \]

\[ = V \sum_{i=1}^{b} p_i R_i \]
Expected systemic loss index for Mexico

*with Serafin Martinez-Jaramillo and team at Banco de Mexico, 2014
Expected systemic loss index

- expected losses per year within country in case of severe default and NO bailout
  → rational decision on bailouts
- allows to compare countries
- allows to compare situation of country over time
  → are policy measures taking action in Spain? in Greece?
Expected systemic loss index: error

![Graph showing expected systemic loss index over time, with approximate and exact values depicted.](image-url)
Observation

Systemic risk of a node changes with every transaction
Austria all interbank loans

LOAN SIZE vs. SYST. RISK INCREASE

note orders of magnitude!
Mexican data

\[ \Delta E L^{syst} > \Delta E L^{credit} \rightarrow \text{defaults do not only affect lenders but involves third parties} \]
systemic risk is an externality
Management of systemic risk

• Systemic risk is a network property to large extent

• Manage systemic risk: re-structure financial networks such that cascading failure becomes unlikely, ideally impossible
systemic risk management

= re-structure networks
Systemic risk elimination

- systemic risk spreads by borrowing from risky agents
- how risky is a transaction? → increase of expected syst. loss
- ergo: restrict borrowing from those with high DebtRank

→ tax those transactions that increase systemic risk
Systemic risk tax

- tax transactions according to their systemic risk contribution
  → agents look for deals with agents with low systemic risk
  → liability networks *re-arrange* → eliminate cascading

No one should pay the tax – tax serves as incentive to re-structure networks

- size of tax = expected systemic loss of transaction (government is neutral)
- if system is risk free: no tax
- credit volume should not be affected by tax
Self-stabilisation of systemic risk tax

- those who can not lend become systemically safer
- those who are safe can lend and become unsafer
- → new equilibrium where systemic risk is distributed evenly across the network (cascading minimal)

→ self-organized critical
To test efficacy of tax: Crisis Macro-Financial Simulator (schematic)
The agents

- **firms**: ask bank for loans: random size, maturity $\tau$, $r^{f-loan}$
  → firms sell products to households: realise profit/loss
  → if surplus → deposit it bank accounts, for $r^{f-deposit}$
  → firms are bankrupt if insolvent, or capital is below threshold
  → if firm is bankrupt, bank writes off outstanding loans

- **banks** try to provide firm-loans. If they do not have enough
  → approach other banks for interbank loan at interest rate $r^{ib}$
  → bankrupt if insolvent or equity capital below zero
  → bankruptcy may trigger other bank defaults

- **households** single aggregated agent: receives cash from firms (through firm-loans) and re-distributes it randomly in banks (household deposits, $r^{h}$), and among other firms (consumption)
For comparison: implement Tobin-like tax

- tax all transactions regardless of their risk contribution
- 0.2% of transaction (∼ 5% of interest rate)
Simulations: measure losses, cascades and efficiency

- total losses to banks resulting from a default/cascade
- cascade size: number of defaulting banks in systemic event
- credit volume: total credit volume in interbank market
Comparison of three schemes

- No systemic risk management
- Systemic Risk Tax (SRT)
- Tobin-like tax
Model results: Systemic risk profile

Austria

Model

(a) BANK SYST. RISK FACTOR

(b) BANK SYST. RISK FACTOR

- no tax
- tobin tax
- systemic risk tax
Model results: Systemic risk of individual loans

Austria

Model

LOAN SIZE

SYST. RISK INCREASE

no tax
tobin tax
systemic risk tax

LOAN SIZE

SYST. RISK INCREASE
Model results: Distribution of losses

![Graph showing distribution of losses for different tax scenarios: no tax, Tobin tax, and systemic risk tax. The graph illustrates how SRT eliminates systemic risk.]

SRT eliminates systemic risk. How?
Model results: Cascading is suppressed
Model results: Credit volume

Tobin tax reduces risk by reducing credit volume
Implementation in reality

- Bank $i$ requests loan of size $L_{ij}$ from bank $j$
- Bank $j$ provides loan for interest $I(L_{ij})$
- Central Bank computes $\text{SRT}(L_{ij})$ for transaction
- Cost for loan with bank $j$: $I(L_{ij}) + \text{SRT}(L_{ij})$
- Bank $i$ asks other bank $k$ for same transaction $L_{ik} = L_{ij}$
- Costs for loan with bank $k$: $I(L_{ik}) + \text{SRT}(L_{ik})$
- Bank $i$ choses transaction partner for which costs are minimal
Challenges – what could be wrong?

• **SRT is pro-cyclical** – feedback: SRT hits most risky banks hardest. Needed: ramp-up phase. Once system is in low-risk equilibrium, there are practically no pro-cyclical effects.

• **SRT is useless if not all countries participate** – arbitrage possibilities for non-participating countries – same as for any transaction tax.

• **Basel III takes care of Systemic Risk?**

• **the interbank network is not the relevant one** – role of derivatives, mutual cross-holdings, overlapping pfs, etc. → apply SRT to other multiplex layers.
Mathematical proof:

SR-free equilibrium under SRT exists
Basel III
Basel III

- Indicator approach: **five categories** (equal weights $\omega^i$): size, interconnectedness, financial institution infrastructure, cross-jurisdictional activity and complexity. Sub-indicators (equal weights)

\[
S_j = \sum_{i \in I} \omega^i \frac{D^i_j}{\sum_B D^i_j} \times 10,000
\]

<table>
<thead>
<tr>
<th>Bucket</th>
<th>Score range</th>
<th>Bucket thresholds</th>
<th>Higher loss-absorbency requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>D-E</td>
<td>530-629</td>
<td>3.50%</td>
</tr>
<tr>
<td>4</td>
<td>C-D</td>
<td>430-529</td>
<td>2.50%</td>
</tr>
<tr>
<td>3</td>
<td>B-C</td>
<td>330-429</td>
<td>2.00%</td>
</tr>
<tr>
<td>2</td>
<td>A-B</td>
<td>230-329</td>
<td>1.50%</td>
</tr>
<tr>
<td>1</td>
<td>Cutoff point-A</td>
<td>130-229</td>
<td>1.00%</td>
</tr>
</tbody>
</table>
• Cross-jurisdictional activity (20%)
  Cross-jurisdictional claims 10%
  Cross-jurisdictional liabilities 10%
  Total exposures for use in Basel III leverage ratio 20%

• Size (20%)
  Intra-financial system assets 6.67%
  Intra-financial system liabilities 6.67%
  Securities outstanding 6.67%
  Assets under custody 6.67%

• Interconnectedness (20%)
  Payments activity 6.67%
  Underwritten transactions in debt and equity markets 6.67%
  (Notional) OTC derivatives 6.67%

• Substitutability / financial institution infrastructure (20%)
  Level 3 assets 6.67%
  Trading and available-for-sale securities 6.67%

• Complexity (20%)
  (Notional) OTC derivatives 6.67%
  Level 3 assets 6.67%
Basel III

- **Size**: total exposures of banks
- **Interconnectedness**: use directed and weighted networks
- **Substitutability/financial institution infrastructure**: payment activity of banks. The payment activity is measured by the sum of all outgoing payments of banks.
- **Complexity**: not modelled (weight 0)
- **Cross-jurisdiction activity**: not modelled (weight 0)
Basel III is does not reduce SR!

(a) Total losses to banks ($L$)

(b) Cascade sizes ($C$)

(c) Transaction volume IB market ($V$)
Basel III works under tremendous costs
Basel III re-distributes systemic risks

(b)

- Blue: Basel III indicator
- Red: Basel III indicator (weight on liabilities)
- Yellow: Basel III indicator (weight on assets)
Part III: Financial multiplex networks
Systemic risk multiplex of Mexico Sep 30 2013

layer 1: derivatives network

layer 2: network of cross holdings

layer 3: foreign exchange exposures

layer 4: network of deposits and loans

layer 5: combined exposures
Size of exposures in the various layers

distribution of exposure size (in Mex $) distribution
data aggregated over Jan 2 2007 to May 30 2013
Interactions between layers (markets)

Jaccard coefficient: \( J_{\alpha \beta} \)

correlations: exposure \( \sum_i L_{ij}^\alpha \), liabilities \( \sum_j L_{ij}^\alpha \), DebtRank \( R \)
Risk profile in the various layers

systemic risk profile for different layers
DebtRank $\hat{R}_i^\alpha$ stacked for banks. Jan 2, 2007 – May 30, 2013
Overlapping portfolios

banks ... blue, assets ... red
Overlapping portfolios (preliminary)
Expected systemic losses for every transaction

\[ \Delta E L^{\text{syst}} > \Delta E L^{\text{credit}} \rightarrow \text{defaults do not affect lender only but involves third parties (all exposures 2007–2013)} \]
Conclusions

- Systemic risk is a network property – endogenously created
- Can be measured for each institution / transaction: DebtRank
- Can be eliminated by SRT; networks don’t allow for cascading
- SRT should not be payed! – evasion re-structures networks
- SRT does not reduce credit volume; re-ordering transactions
- Basel III as planned does not work – 3 fold works – costly
- SR requires a multiplex network framework
- Expected Systemic Loss Index: compare countries, over time
- SR tax is technically feasible
Mexican data collaborators

Sebastian Poledna
Peter Klimek
Serafin Martinez-Jamarillo
Jose-Luis Molina Balboa
Marco van der Leij
Alternatives to systemic risk tax

- Mandatory CDS
- Markose: taxes banks — not transactions — according to eigenvalue centrality

**Problem 1** eigenvector is not economically reasonable number

**Problem 2** blind to cycles in contract networks

**Problem 3** absurd size (up to 30% of capital)

- Tax size: misses small SR institutions, SR improvement at tremendous economic cost
Markose proposal in macro-financial ABM

Losses

Output (GDP)

<table>
<thead>
<tr>
<th></th>
<th>No tax</th>
<th>SRT</th>
<th>SST ($\alpha=0.1$)</th>
<th>SST ($\alpha=0.67$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>128.458 ± 1.792</td>
<td>128.382 ± 2.038</td>
<td>127.506 ± 3.278</td>
<td>106.877 ± 20.706</td>
</tr>
<tr>
<td>Unemployment</td>
<td>0.0017 ± 0.0102</td>
<td>0.0020 ± 0.0121</td>
<td>0.0059 ± 0.0204</td>
<td>0.1520 ± 0.1533</td>
</tr>
<tr>
<td>Credits (firms)</td>
<td>128.174 ± 18.990</td>
<td>121.435 ± 17.303</td>
<td>120.193 ± 19.397</td>
<td>87.943 ± 29.958</td>
</tr>
<tr>
<td>Interest (firms)</td>
<td>0.0238 ± 0.0015</td>
<td>0.0243 ± 0.0016</td>
<td>0.0241 ± 0.0017</td>
<td>0.0248 ± 0.0023</td>
</tr>
</tbody>
</table>
Statistical measures

- CoVAR: descriptive – not predictive!
- SES, SRISK: related to leverage and size
- DIP: market based – markets do not see NW-based SR

**pro** data publicly available, easy to implement

**contra** ’conditional’ hard to define without knowledge of networks, descriptive, non-predictive