

The Relationship between Network Topology and Contagion – A Panel Data Approach for ARTIS

Claus Puhr, Stefan W. Schmitz, OeNB

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Research questions

- Based on Schmitz / Puhr (2007)
- Large variation of operational shock across scenarios & days
- How many accounts are systemically important?
- What explains the large variations across scenarios and/or days?
- Do network indicators at the node level and/or network level have explanatory value?

Methods

- **Network theory**
 - Robustness studies
 - Typology of flow processes
 - Measures of network structure
 - Network level (44) & node level (stricken bank) (71)
- **Simulations**
 - Simulations of operational shocks generate contagion
- **Panel econometrics**
 - Variations of contagion across scenarios and/or days

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Network theory

- Robustness studies (Albert et al. 1999, 2000: Internet)
 - Nature of shock: removal of nodes and links from network
 - Measure of impact: Connectivity measured by size of largest cluster and average path length
- Robustness in ARTIS
 - ARTIS is a physically complete network
 - Flow of liquidity not equal to flow of information in the internet
 - Connectivity inappropriate conceptualisation of network stability
 - Incoming links to stricken account not removed

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Network theory

- Typology of flow processes
 - Appropriate measure of network structure?
 - Albert et al. (1999, 2000: Internet) – average path length
 - Boss et al. (2004: Interbank liabilities) – betweenness centrality
 - Optimal measure depends on flow process (Borgatti 2005)
 - Route/transfer characteristics
 - Liquidity follows a walk and is transferred

Network theory

- Typology of flow processes
 - Appropriate measure of network structure?
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 - Optimal measure depends on flow process (Borgatti 2005)

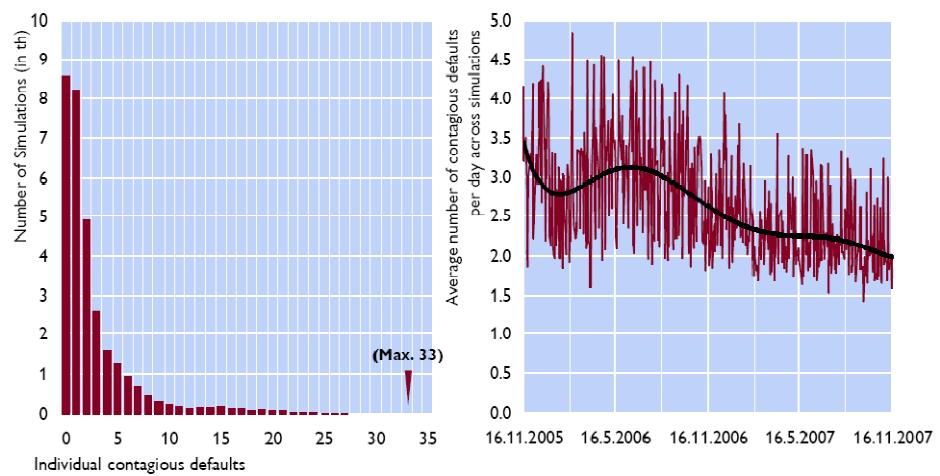
Measures based on shortest paths inappropriate
(e. g. average path length and betweenness centrality)
→ Degree measures are better suited!

Simulations

- Assumption: one day incapacitation to submit payments
- Sample period: 16 November 2005 to 16 November 2007 (497 days)
- 63 scenarios
 - 50 banks which are in GSAC on all days in the sample period
 - 13 transfer accounts which are part of the system on all days
- Matlab based simulation tool
 - Stop-sending rule
 - Direct debit
- 31 311 simulations (63×497) with 650 mn transactions

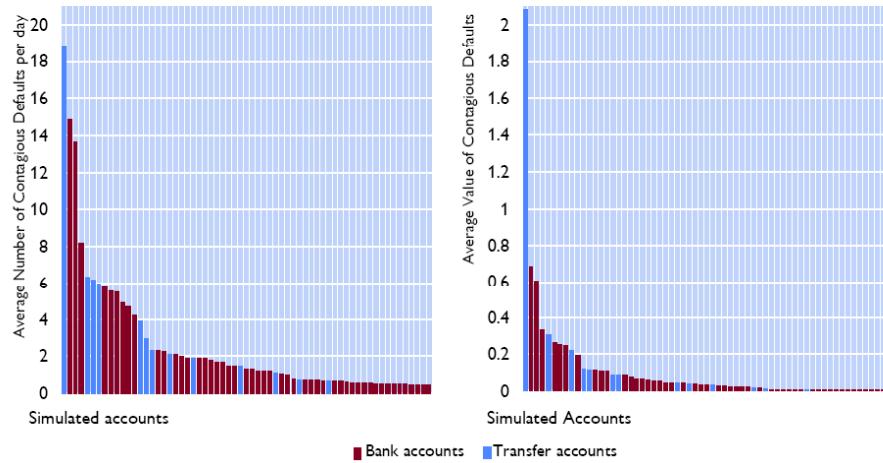
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Simulation results



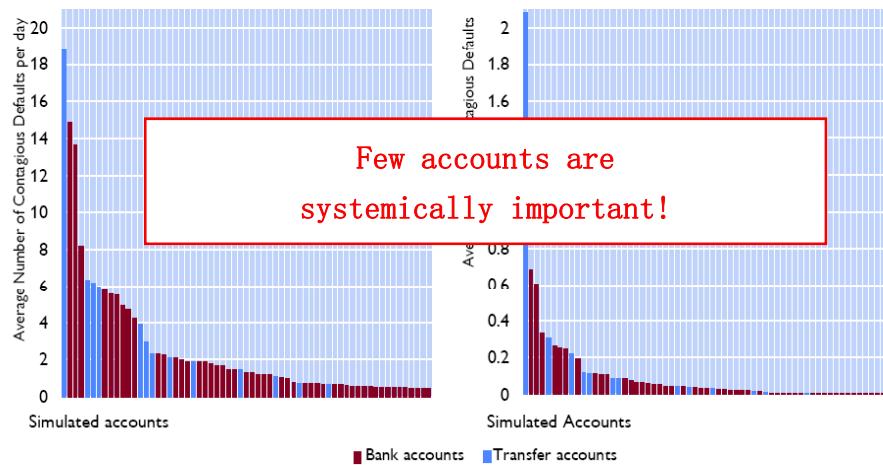
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Simulation results

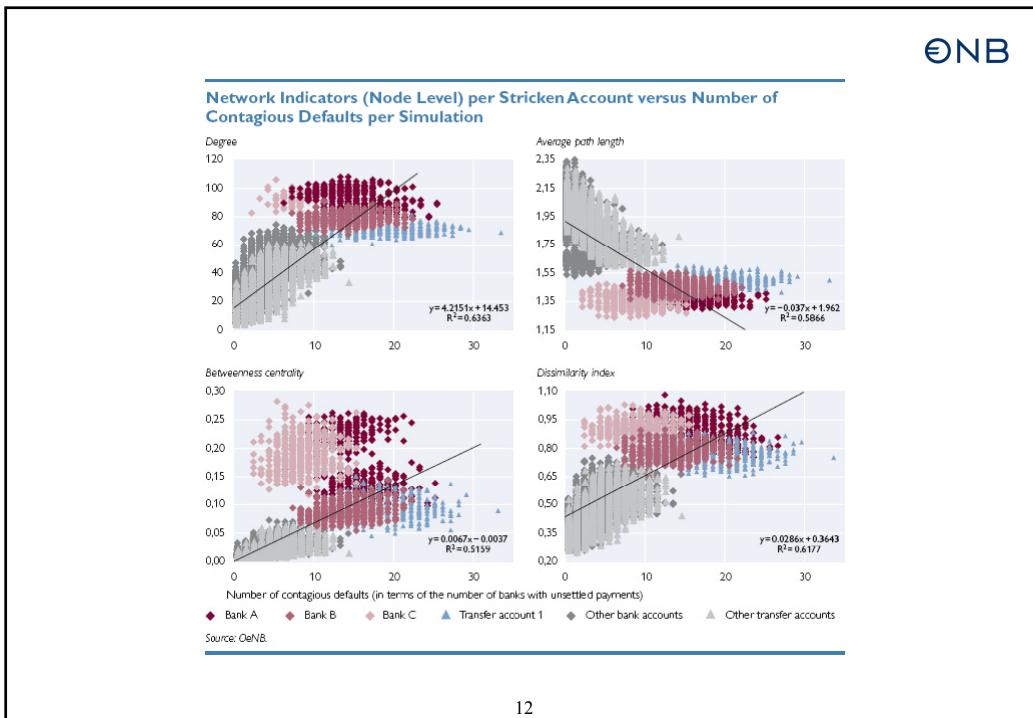
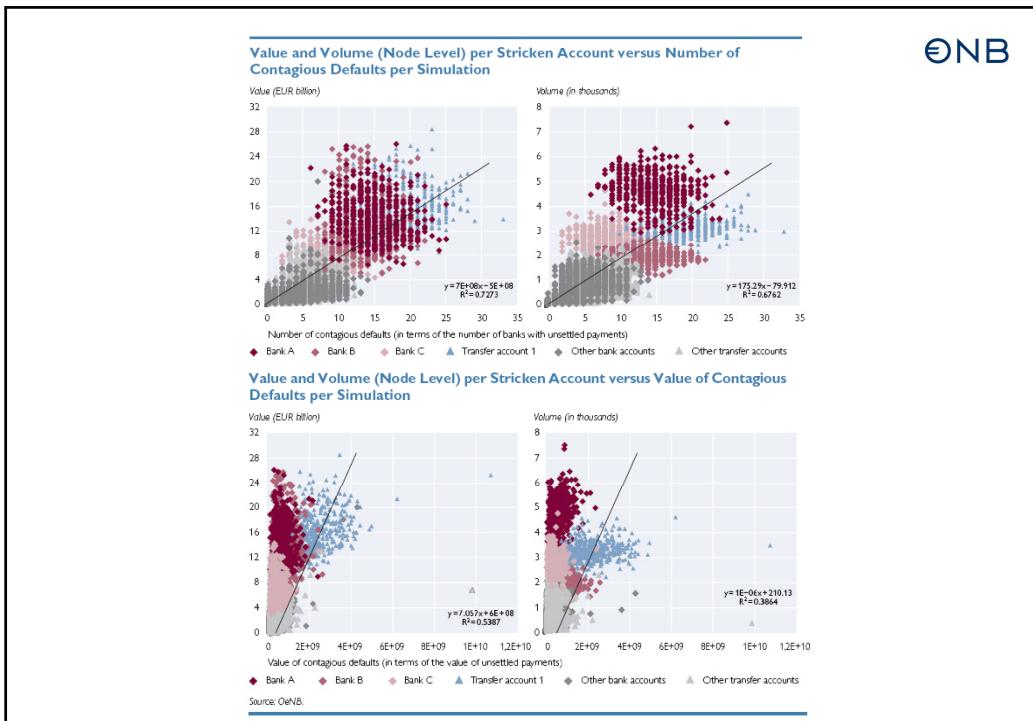


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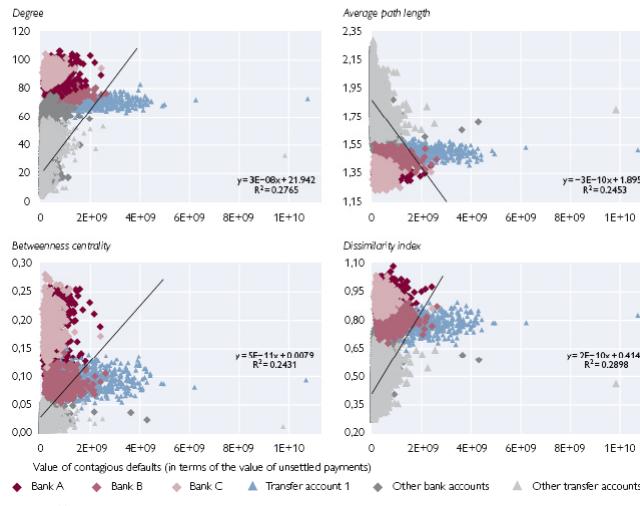
Simulation results



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Network Indicators (Node Level) per Stricken Account versus Value of Contagious Defaults per Simulation



Source: OeNB.

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Correlation between volume, value and network indicators

| | Volume | Value | Avg. PL | Degree | Conn. | Clust. | Btw. C. | Dissim. |
|---------|--------|-------|---------|--------|-------|--------|---------|---------|
| Volume | 100% | 89% | -77% | 84% | 83% | -57% | 89% | 85% |
| Value | | 100% | -70% | 76% | 75% | -52% | 77% | 78% |
| Avg. PL | | | 100% | -96% | -97% | 62% | -79% | -85% |
| Degree | | | | 100% | 99% | -72% | 85% | 95% |
| Conn. | | | | | 100% | -72% | 85% | 93% |
| Clust. | | | | | | 100% | -56% | -78% |
| Btw. C. | | | | | | | 100% | 87% |
| Dissim. | | | | | | | | 100% |

Source: OeNB. Average Path Length (Avg. PL), Connectivity (Conn.), Clustering Index (Clust.), Betweenness Centrality (Btw. C.), Dissimilarity Index (Dissim.).

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Dependent variables

- Measures of contagion (excl. stricken bank)
 - Value of unsettled payments at end of day
 - Number of unsettled payments at end of day
 - Number of banks with unsettled payments at end of day

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Independent variables

- Network level (constant across panels but not across time [Z])
 - Aggregate liquidity
(BoD balances + unencumbered collateral across banks)
 - Network indicators at the network level
- Node level (varies across panels and across time [X])
 - Liquidity loss due to operational problem at stricken bank
(liquidity sink/drain, unreceived payments)
 - Network indicators at the node level
- Dummy for transfer accounts (D×unreceived payments)

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Descriptive statistics – dependent variables

| variable | Mean | Std. Dev. | Min | Max | observations |
|---------------------------------------|----------|----------------------------------|-----------------------------|----------------------------------|--------------------------------|
| simnum~s overall between within | 2.607678 | 3.765892 3.534751 1.373103 | 0 .4507042 -.6.301779 | 33 18.85714 16.75053 | N = 31311 n = 63 T = 497 |
| simque~m overall between within | 7.554757 | 21.71519 14.0254 16.67194 | 0 .4507042 -55.94424 | 1172 76.49899 1145.718 | N = 31311 n = 63 T = 497 |
| simque~l overall between within | 1.12e+08 | 3.35e+08 2.84e+08 1.81e+08 | 0 3680408 -1.54e+09 | 1.07e+10 2.08e+09 9.79e+09 | N = 31311 n = 63 T = 497 |

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Descriptive statistics – aggregate liquidity

| variable | Mean | Std. Dev. | Min | Max | observations |
|---------------------------------------|----------|---------------------------|----------------------------------|----------------------------------|--------------------------------|
| liqbode overall between within | 7.47e+09 | 8.43e+08 0 8.43e+08 | 5.49e+09 7.47e+09 5.49e+09 | 1.13e+10 7.47e+09 1.13e+10 | N = 31311 n = 63 T = 497 |
| liqcol~l overall between within | 1.08e+10 | 2.89e+09 0 2.89e+09 | 6.10e+09 1.08e+10 6.10e+09 | 2.53e+10 1.08e+10 2.53e+10 | N = 31311 n = 63 T = 497 |
| Liquid~y overall between within | 1.83e+10 | 3.23e+09 0 3.23e+09 | 1.17e+10 1.83e+10 1.17e+10 | 3.24e+10 1.83e+10 3.24e+10 | N = 31311 n = 63 T = 497 |

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Descriptive statistics – liquidity loss

| variable | | Mean | Std. Dev. | Min | Max | Observations |
|----------|------------------------------|-----------------|------------------|-----------------|-----------------|-----------------|
| Liquid~s | overall between within | 1.39e+09 | 3.07e+09 | 12032 | 2.86e+10 | N = 31310 |
| | | 2.92e+09 | 7869281 | 1.57e+10 | 1.96e+10 | n = 63 |
| | | 1.02e+09 | -7.11e+09 | | | T-bar = 496.984 |
| simliq~n | overall between within | 7.23e+08 | 1.69e+09 | 0 | 1.60e+10 | N = 31310 |
| | | 1.59e+09 | 452661.6 | 8.80e+09 | 1.00e+10 | n = 63 |
| | | 6.16e+08 | -3.91e+09 | | | T-bar = 496.984 |
| simliq~k | overall between within | 6.67e+08 | 1.53e+09 | 524 | 1.29e+10 | N = 31310 |
| | | 1.45e+09 | 1026011 | 6.92e+09 | 9.59e+09 | n = 63 |
| | | 5.02e+08 | -3.32e+09 | | | T-bar = 496.984 |

Descriptive statistics – network indicators node level

| variable | | Mean | Std. Dev. | Min | Max | Observations |
|----------|------------------------------|-----------------|------------------|-----------------|---------------|--------------|
| nodede~e | overall between within | 25.44499 | 19.89985 | 2 | 105 | N = 31311 |
| | | 19.83007 | 6.428571 | 89.84708 | 105 | n = 63 |
| | | 3.000303 | 10.34036 | 43.26994 | | T = 497 |
| nodeco~y | overall between within | .1930355 | .1510905 | .0153 | .7949 | N = 31311 |
| | | .1503863 | .0490459 | .6821545 | .7949 | n = 63 |
| | | .0238868 | .075481 | .3372814 | | T = 497 |
| nodeav~h | overall between within | 1.86558 | .1817904 | 1.2137 | 2.3356 | N = 31311 |
| | | .1782929 | 1.328216 | 2.102365 | 2.3356 | n = 63 |
| | | .0419877 | 1.67934 | 2.169161 | | T = 497 |
| nodecl~x | overall between within | .5401702 | .2014584 | .1333 | 1 | N = 31311 |
| | | .1873986 | .1753167 | .9800881 | 1 | n = 63 |
| | | .0776117 | .1056149 | 1.013537 | | T = 497 |
| nodebe~y | overall between within | .013652 | .0349052 | 0 | .2761 | N = 31311 |
| | | .0340873 | 6.04e-07 | .1833795 | .2761 | n = 63 |
| | | .0086509 | -.0796849 | .1063725 | | T = 497 |
| nodedi~x | overall between within | .4387912 | .1369233 | .2603 | 1.0754 | N = 31311 |
| | | .13323 | .312793 | .9046616 | 1.0754 | n = 63 |
| | | .0357625 | .281154 | .626754 | | T = 497 |

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Descriptive statistics – network indicators network level

| Variable | Mean | Std. Dev. | Min | Max | Observations |
|---------------------------------|-----------------|-----------|---------|----------|--------------|
| netavg~e overall between within | 12.36032 | .3990639 | 11.2609 | 14.35 | N = 31311 |
| | | .3990639 | 0 | 12.36032 | n = 63 |
| | | | 11.2609 | 12.36032 | T = 497 |
| | | | | 14.35 | |
| netcon~y overall between within | .0375596 | .0027451 | .0294 | .0462 | N = 31311 |
| | | .0027451 | 0 | .0375596 | n = 63 |
| | | | .0294 | .0462 | T = 497 |
| netavg~h overall between within | 2.546561 | .0594155 | 2.4025 | 2.6833 | N = 31311 |
| | | .0594155 | 0 | 2.546561 | n = 63 |
| | | | 2.4025 | 2.546561 | T = 497 |
| | | | | 2.6833 | |
| netavgc~ overall between within | .4382753 | .0279867 | .3612 | .5217 | N = 31311 |
| | | .0279867 | 0 | .4382753 | n = 63 |
| | | | .3612 | .5217 | T = 497 |
| netavg~y overall between within | .0047867 | .0002584 | .0038 | .0055 | N = 31311 |
| | | .0002584 | 0 | .0047867 | n = 63 |
| | | | .0038 | .0055 | T = 497 |
| netavg.. overall between within | 1.269688 | .9284118 | .5946 | 5.228 | N = 31311 |
| | | .9284118 | 0 | 1.269688 | n = 63 |
| | | | .5946 | 5.228 | T = 497 |

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Panel approach – the model

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_{63} \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{63} \end{bmatrix} \beta_1 + [Z] \beta_2 + \begin{bmatrix} \nu_1 \\ \nu_2 \\ \vdots \\ \nu_{63} \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_{63} \end{bmatrix}$$

$$E[\varepsilon_{it} | x_i, \nu_i] = 0 \quad T = 1 \dots 497, \quad N = 1 \dots 63.$$

$$Var[\varepsilon_{it} | x_i, \nu_i] = \sigma^2 I_T$$

$$Cov[\varepsilon_{it}, \varepsilon_{js}] = 0 \quad if \quad t \neq s \quad or \quad i \neq j.$$

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Panel approach – the assumptions

- Cross-panel conditional homoskedasticity
 - Variance of error terms constant across panels (and across time)
- Serial independence
 - Error terms are serially uncorrelated within panels
- Cross-panel independence
 - Error terms are independent across panels
- Strict exogeneity
 - Error terms and explanatory variables are independent

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Basic models used for tests

Model 1

$$\begin{aligned} simdefaults_{it} = & \alpha + \beta_1 Liquidity_t + \beta_2 simunrvol_{it} + \beta_3 TransUnrVol_{it} + \\ & + \beta_4 nodeavgpath_{it} + \beta_5 netavgpath_t + u_i + \varepsilon_{it} \end{aligned}$$

Model 2

$$\begin{aligned} simqueuednum_{it} = & \alpha + \beta_1 Liquidity_t + \beta_2 simunrdvol_{it} + \beta_3 TransUnrVol_{it} + \\ & + \beta_4 nodeavgpath_{it} + \beta_5 netavgpath_t + u_i + \varepsilon_{it} \end{aligned}$$

Model 3

$$\begin{aligned} simqueuedvol_{it} = & \alpha + \beta_1 Liquidity_t + \beta_2 simunrvol_{it} + \beta_3 TransUnrVol_{it} + \\ & + \beta_4 nodeavgpath_{it} + \beta_5 netavgpath_t + u_i + \varepsilon_{it} \end{aligned}$$

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Assumption of conditional homoscedasticity across panels

- Likelihood ratio test

- Compares log-likelihoods under restricted and unrestricted model based on iterated generalised least square estimates.

| | | |
|---------|--------------------------|--------------|
| Model 1 | LR chi2 (62) = 18501.32 | Prob. = 0.00 |
| Model 2 | LR chi2 (62) = 103014.77 | Prob. = 0.00 |
| Model 3 | LR chi2 (62) = 74980.00 | Prob. = 0.00 |

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Assumption of conditional homoscedasticity across panels

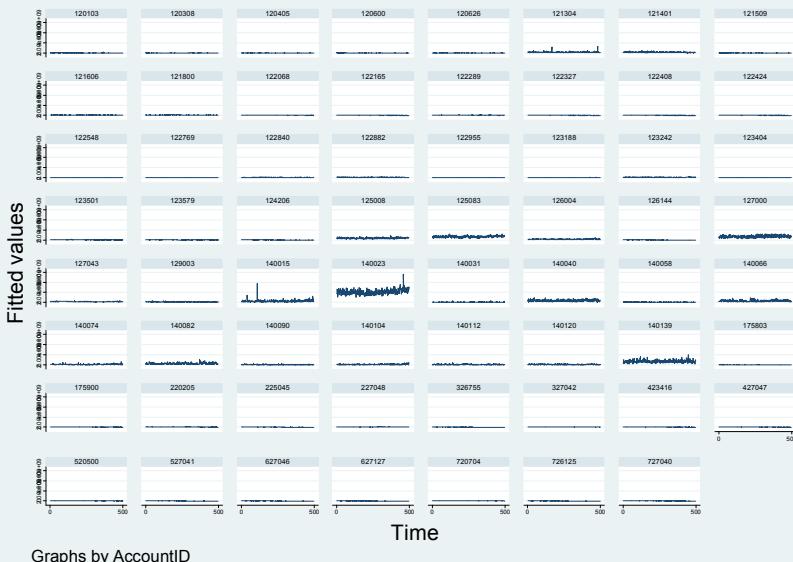
- Likelihood ratio test

- Compares log-likelihoods under restricted and unrestricted model based on iterated generalised least square estimates.

| | | |
|---------|--------------------------|--------------|
| Model 1 | LR chi2 (62) = 18501.32 | |
| Model 2 | LR chi2 (62) = 103014.77 | |
| Model 3 | LR chi2 (62) = 74980.00 | Prob. = 0.00 |

Assumption of conditional
homoscedasticity rejected

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Assumption of serial independence

- Wooldridge test
 - Based on residuals of regressions in first differences which are then regressed on lagged value t-1
 - Test is robust to conditional heteroskedasticity

| | | |
|---------|---------------------|--------------|
| Model 1 | $F(1, 62) = 14.388$ | Prob. = 0.00 |
| Model 2 | $F(1, 62) = 3.076$ | Prob. = 0.08 |
| Model 3 | $F(1, 62) = 23.636$ | Prob. = 0.00 |

Assumption of serial independence

- Wooldridge test

- Based on residuals of regressions in first differences which are then regressed on lagged value t-1
- Test is robust to conditional heteroskedasticity

| | | |
|---------|---------------------|--------------|
| Model 1 | $F(1, 62) = 14.388$ | Prob. = 0.00 |
| Model 2 | $F(1, 62) = 3.07$ | Prob. = 0.07 |
| Model 3 | $F(1, 62) = 3.07$ | Prob. = 0.00 |

Assumption of serial independence rejected

Assumption of cross-panel independence

- Pesaran, Friedman, Frees tests

| | | |
|---------|--|--|
| Model 1 | Frees = 11.116 Pesaran = 363.108 Friedman = 11728.05 | Prob. = 0.00 Prob. = 0.00 Prob. = 0.00 |
| Model 2 | Frees = 7.06 Pesaran = 147.08 Friedman = 7378.70 | Prob. = 0.00 Prob. = 0.00 Prob. = 0.00 |
| Model 3 | Frees = 4.81 Pesaran = 120.80 Friedman = 5744.16 | Prob. = 0.00 Prob. = 0.00 Prob. = 0.00 |

Assumption of cross-panel independence

- Pesaran, Friedman, Frees tests

| | | |
|---------|--|--|
| Model 1 | Frees = 11.116 Pesaran = 363.108 Friedman = 11728.05 | Prob. = 0.00 Prob. = 0.00 Prob. = 0.00 |
| Model 2 | Frees = 7.06 Pesaran = 11.80 Friedman = 5744.16 | Prob. = 0.00 Prob. = 0.00 Prob. = 0.00 |
| Model 3 | | |

Assumption of cross-sectional
independence rejected

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Random- versus fixed-effects

- High correlation btw individual level effects and explanatory variables
- Breusch-Pagan LR test of random effects
 - Compares log-likelihoods under restricted and unrestricted model based on iterated generalised least square estimates

| | | |
|---------|-------------------|--------------|
| Model 1 | LR test = 3.06E05 | Prob. = 0.00 |
| Model 2 | LR test = 4.33E04 | Prob. = 0.00 |
| Model 3 | LR test = 2.30E05 | Prob. = 0.00 |

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Random- versus fixed-effects

- High correlation btw individual level effects and explanatory variables
- Breusch-Pagan LR test of random effects
 - Compares log-likelihoods under restricted and unrestricted model based on iterated generalised least square estimates

| | | |
|---------|--------------------|--------------|
| Model 1 | LR test = 3.06E05 | Prob. = 0.00 |
| Model 2 | LR test = 4.32E-05 | |
| Model 3 | | Prob. = 0.00 |

Random-effects rejected

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Assumption of strict exogeneity

- Fundamental assumption
 - Error terms are not influenced by past, current or future values of explanatory variables
 - Values of explanatory variables are not influenced by past, current or future values of error terms
- Simulation design ensures strict exogeneity
 - Values of explanatory variables are empirical observations
 - Error terms cannot influence values of explanatory variables
 - E.g. banks cannot adjust liquidity holdings, node or network characteristics in response to observed error terms

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Estimation procedure

- Estimate fixed-effects model (yields inconsistent standard errors)
- Correct for cross-section conditional heteroskedasticity, autocorrelation and cross-section-dependence
- Prais-Winsten regression, PCSE (Panel-Corrected Standard Errors)
 - Accounts for heteroskedasticity and cross-panel correlation
 - Additional option panel-specific autocorrelation
- Estimate models 1 to 3 without network indicators
 - Add individual network indicators at node- and network-level
 - One at a time, due to high correlation between network indicators

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Questions

- Exploratory analysis
 - What explains the variation of contagion?
 - Across panels
 - Across time
 - What is the explanatory value of network indicators?
 - What is the significance of network indicators?

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| # contagious bank defaults | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | B |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|----------|
| Constant | 3.28 | 4.02 | 3.38 | 2.32 | 14.73 | 6.97 | 4.63 | -0.93 | |
| Liquidity | -1.05E-10 | -9.69E-11 | -9.91E-11 | -8.39E-10 | -9.31E-11 | -9.40E-11 | -9.70E-11 | -1.18E-10 | |
| SimUnrVol | 1.65E-09 | 1.66E-09 | 7.77E-10 | 8.06E-10 | 1.01E-09 | 1.43E-09 | 1.07E-09 | 9.37E-10 | |
| Transfer*SimUnrVol | 59.21 | 58.92 | 28.64 | 30.80 | 38.61 | 55.18 | 0.00 | 33.42 | |
| | 2.51E-10 | 2.52E-10 | 6.12E-10 | 6.00E-10 | 5.27E-10 | 2.58E-10 | 5.44E-10 | 5.06E-10 | |
| | 8.99 | 8.93 | 23.28 | 22.92 | 20.57 | 9.66 | 19.29 | 19.42 | |
| Nodedegree | | | 9.20E-02 | | | | | | |
| | | | 59.92 | | | | | | |
| Nodeconnectivity | | | | 1.22E+01 | | | | | |
| | | | | 59.88 | | | | | |
| Nodeavgpath | | | | | -8.09E+00 | | | | |
| | | | | | -56.71 | | | | |
| Nodeclusterindex | | | | | | -4.00E+00 | | | |
| | | | | | | -51.65 | | | |
| Nodebetweenness | | | | | | | 3.38E+01 | | |
| | | | | | | | 26.37 | | |
| Nodedissimilarity | | | | | | | | 1.11E+01 | |
| | | | | | | | | 40.07 | |
| Netvolume | | | -1.88E-11 | | | | | | |
| | | | -7.76 | | | | | | |
| Netavgdegree | | | | -1.60E-01 | | | | | |
| | | | | -2.24 | | | | | |
| Netconnectivity | | | | | -3.25E+01 | | | | |
| | | | | | -3.25 | | | | |
| Netavgpath | | | | | | 1.51E+00 | | | |
| | | | | | | 2.52 | | | |
| Netavgclusterindex | | | | | | | -3.60E+00 | | |
| | | | | | | | -3.42 | | |
| Netavgbetweenness | | | | | | | | -3.00 | |
| | | | | | | | | 0.82 | |
| Netavgdissimilarity | | | | | | | | | 3.00E-02 |
| R ² | 69.23 | 69.35 | 69.96 | 72.41 | 71.58 | 70.88 | 66.54 | 68.69 | |
| Relative impact of Transfer Account (in (in %)) | 15% | 15% | 79% | 74% | 52% | 18% | 51% | 54% | |
| | | | | | 57 | | | | |

| # contagious unsettled payments | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | B |
|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|----------|
| Constant | 7.32 | 9.90 | -3.06 | 0.57 | 35.54 | 12.55 | 4.73 | -0.36 | |
| | 7.25 | 10.67 | -0.93 | 0.34 | 6.39 | 6.93 | 2.13 | -0.35 | |
| Liquidity | -2.79E-10 | -2.49E+00 | -2.70E-10 | -1.97E-10 | -2.25E-10 | -2.52E-10 | -2.59E-10 | -2.91E-10 | |
| | -5.65 | -5.44 | -6.18 | -4.57 | -4.75 | -5.43 | -5.29 | -6.24 | |
| SimUnrVol | 6.61E-09 | 6.67E-09 | 4.97E-09 | 4.94E-09 | 5.32E-09 | 6.29E-09 | 5.59E-09 | 5.41E-09 | |
| | 41.91 | 41.84 | 24.31 | 24.17 | 28.22 | 38.61 | 22.59 | 26.62 | |
| Transfer*SimUnrVol | 2.40E-09 | 2.38E-09 | 3.10E-09 | 2.95E-09 | 2.45E-09 | 2.91E-09 | 2.84E-09 | 2.84E-09 | |
| | 8.36 | 8.29 | 10.53 | 10.55 | 10.08 | 8.49 | 9.52 | 9.72 | |
| Nodedegree | | | 1.80E-01 | | | | | | |
| | | | 13.51 | | | | | | |
| Nodeconnectivity | | | | 2.46E+01 | | | | | |
| | | | | 13.85 | | | | | |
| Nodeavgpath | | | | | -1.71E+01 | | | | |
| | | | | | -13.92 | | | | |
| Nodeclusterindex | | | | | | -6.25E+00 | | | |
| | | | | | | -10.84 | | | |
| Nodebetweenness | | | | | | | 5.40E+01 | | |
| | | | | | | | 5.65 | | |
| Nodedissimilarity | | | | | | | | 1.90E+01 | |
| | | | | | | | | 10.02 | |
| Netvolume | | | -6.67E-11 | | | | | | |
| | | | -8.15 | | | | | | |
| Netavgdegree | | | | 5.10E-01 | | | | | |
| | | | | 1.93 | | | | | |
| Netconnectivity | | | | | 3.09E+01 | | | | |
| | | | | | 0.86 | | | | |
| Netavgpath | | | | | | 1.21E+00 | | | |
| | | | | | | 0.56 | | | |
| Netavgclusterindex | | | | | | | -5.29E+00 | | |
| | | | | | | | -1.40 | | |
| Netavgbetweenness | | | | | | | | 4.27E+02 | |
| | | | | | | | | 1.09 | |
| Netavgdissimilarity | | | | | | | | | 5.00E-02 |
| | | | | | | | | | 0.52 |
| R ² | 39.79 | 39.81 | 39.90 | 40.01 | 40.02 | 39.77 | 39.72 | 39.67 | |
| Relative impact of Transfer Account (in (in %)) | 36% | 36% | 62% | 63% | 55% | 39% | 52% | 52% | |

| Value of contagious unsettled payments | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | IB |
|---|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----|
| Constant | 5.22E+07 <i>5.30</i> | 7.37E+07 <i>7.16</i> | 2.47E+07 <i>0.59</i> | 3.63E+07 <i>1.70</i> | 2.87E+08 <i>4.08</i> | 5.94E+07 <i>2.65</i> | 4.24E+07 <i>1.44</i> | 5.35E+07 <i>4.59</i> | |
| Liquidity | -2.70E-03 <i>-5.01</i> | -2.19E-03 <i>-4.29</i> | -2.70E-03 <i>-5.08</i> | -2.50E-03 <i>-4.22</i> | -2.10E-03 <i>-3.57</i> | -2.68E-03 <i>-4.77</i> | -2.62E-03 <i>-4.80</i> | -2.72E-03 <i>-4.97</i> | |
| SimUnrVol | 9.56E-02 <i>47.60</i> | 9.60E-02 <i>47.77</i> | 9.22E-02 <i>35.69</i> | 9.04E-02 <i>35.17</i> | 9.09E-02 <i>38.17</i> | 9.72E-02 <i>45.99</i> | 9.65E-02 <i>33.87</i> | 9.56E-02 <i>36.91</i> | |
| Transfer*SimUnrVol | 1.59E-01 <i>34.54</i> | 1.59E-01 <i>34.48</i> | 1.60E-01 <i>34.24</i> | 1.61E-01 <i>34.29</i> | 1.61E-01 <i>34.55</i> | 1.58E-01 <i>34.60</i> | 1.58E-01 <i>33.08</i> | 1.59E-01 <i>34.04</i> | |
| Nodedegree | | 3.33E+05 <i>2.34</i> | | | | | | | |
| Nodeconnectivity | | | 6.85E+07 <i>3.63</i> | | | | | | |
| Nodeavgpath | | | | 5.76E+07 <i>-4.42</i> | | | | | |
| Nodeclusterindex | | | | | 2.78E+07 <i>3.66</i> | | | | |
| Nodebetweenness | | | | | | -4.65E+07 <i>-0.53</i> | | | |
| Nodedissimilarity | | | | | | | 2.52E+06 <i>-0.12</i> | | |
| Netvolume | | 6.20E-04 <i>-5.49</i> | | | | | | | |
| Netavgdegree | | | 1.76E+06 <i>0.52</i> | | | | | | |
| Netconnectivity | | | | 7.28E+07 <i>0.16</i> | | | | | |
| Netavgpath | | | | | 5.32E+07 <i>-1.92</i> | | | | |
| Netavgclusterindex | | | | | | -5.39E+07 <i>-1.11</i> | | | |
| Netavgbetweenness | | | | | | | 1.93E+07 <i>0.36</i> | | |
| Netavgdissimilarity | | | | | | | | 5.25E+05 <i>0.41</i> | |
| R ² | 70.62 | 70.63 | 70.64 | 70.65 | 70.69 | 70.68 | 70.60 | 70.61 | |
| Relative impact of Transfer Account (in %) | 166% | 166% | 174% | 178% | 177% | 163% | 164% | 166% | |

€NB

Results (1/2)

- Explanatory value of models high (40 to 70 per cent)
 - Much higher for between than for within panel variation
- Results robust across specifications & estimation methods
- Higher liquidity reduces contagion effect
- Higher liquidity loss increases contagion effect
 - Impact highest for value of unsubmitted payments
 - Less for liquidity drain and liquidity sink
 - Variable has very high explanatory power
- Transfer accounts cause significantly more contagion

Results (2/2)

- Higher value of transactions in the network reduces contagion
 - Time trend?
- At the network level no indicator is significant in all three models
- At the node level three network indicators are significant in all models
 - Higher node degree and connectivity increase contagion
 - Higher average path length decreases contagion
 - More central nodes cause more contagion
- Additional explanatory value:
 - 3 per cent regarding the number of contagiously defaulting banks
 - Negligible in the other two models

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Summary (1/2)

- Number of systemically important accounts is low
 - 11 transfer accounts & 28 banks cause at least one contagious default on average per day
 - 7 transfer accounts & 17 banks cause at least an average value of contagion of 0.1 per cent of average total value per day
- Network indicators in payment systems
 - Degree seems to be adequate indicator

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Summary (2/2)

- Panel approach yields high explanatory value
 - Higher between scenarios than within
- Most of the variation is explained by:
 - Aggregate liquidity
 - Liquidity loss
 - Impact of transfer accounts
- Some network indicators at node level are significant
- Their explanatory contribution is low

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Definition of network indicators

The *average degree* k of the network is calculated by summing across all (active) links originating from each node (out-degree k_i^{out}) or terminating at each node (in-degree k_i^{in}) and then averaging across nodes:

$$k = \frac{1}{n} \sum_i k_i^{out} = \frac{1}{n} \sum_i k_i^{in} = \frac{m}{n}$$

We calculate the *average path length* for each (active) originating node ℓ_i by averaging across terminating nodes j and then averaged across originating nodes i to derive the average path length ℓ of the entire network.

$$\begin{aligned}\ell_i &= \frac{1}{n-1} \sum_{j \neq i} d_{ij} \\ \ell &= \frac{1}{n} \sum_i \ell_i\end{aligned}$$

Considering the maximum eccentricity \mathcal{E} (the maximum path length between any originating and any terminating node) across nodes defines the *diameter* D :

$$D = \max_i \mathcal{E}_i$$

The *connectivity* of the network is defined by the number of actual directed links m over the number of possible directed links $n(n-1)$.

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Definition of network indicators

An indicator of the distance d_{ij} between nodes is the lowest possible number of links that connects each (active) node i with each other (active) node j in the network. It is referred to as shortest path length.

The *betweenness centrality* $C_B(h)$ of node h provides a measure of how many shortest paths d_{ij} pass through this node. Let $s_{ij}(h)$ be the number of shortest paths between all pairs of nodes i and j that pass through the node h and let S_{ij} the number of all shortest paths between all pairs of nodes i and j then

$$C_B(h) = \sum_{s \neq i \neq j} \frac{s_{ij}(h)}{S_{ij}}.$$

$C_B(h)$ is sometimes normalised by dividing it by the number of pairs of nodes not including the node h . The betweenness centrality of the network is

$$C_B = \frac{1}{n} C_B(h)$$

Definition of network indicators

The *dissimilarity index* of two neighbours nodes i and j in a network is defined as

$$\Delta_{ij} = \sqrt{\frac{\sum_{h \neq i, j}^N [d_{ih} - d_{jh}]^2}{(N-2)}},$$

where d_{ik} are distance measures from nodes i and j to node h . It provides a comparison of the viewpoints of the entire network from the perspective of the all pairs of neighbouring nodes. For the entire network the dissimilarity index is

$$\Delta = \frac{1}{n(n-1)/2} \Delta_{ij}$$

The *clustering coefficient* $C_C(h)$ of an individual node h with k_h neighbours measures how well the latter are connected among each other. The number of potential links between the k_h neighbours is $k_h(k_h - 1)/2$. Let the actual number of nodes between them be E_h so that

$$C_C = \frac{E_h}{k_h(k_h - 1)/2}$$