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An Agent-based model of liquidity and solvency interactions with banks and asset managers

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DISCLAIMER: The views expressed are those of the author and do not necessarily reflect those of the Bank of Canada

FSD-Model Development and Research Division

Agenda

- Objectives and key takeaways
- Model set-up
- Simulations
- Conclusions

Objective

- **Goal:** build the model of funding shock propagation in a system of interacting banks and asset managers, accounting for
  - Contagion in the interbank funding market
  - Fire sales
  - Funding-solvency vicious loop
  - Regulatory risk constraints

- **How?:** agent-based model
  - To work in a complex, multi-dimensional setup, reflecting nature of financial system
  - To study stressful scenarios

Key takeaways

- Model captures:
  - Utilization of liquidity buffers;
  - Interbank funding channel;
  - Amplification effects of funding shocks via fire sales;
  - Relationship between funding cost and solvency;
  - Information (panic) contagion;
  - Network effects of bond cross-holdings in case of solvency defaults
- Findings:
  - Nonlinearities – cliff effects;
  - Changes to the interbank market architecture;
  - (appendix) Cross-border channels;
  - (appendix) Drivers of systemic liquidity risk – dependence on the financial structure;
  - (appendix) Liquidity requirements – mitigation of contagion risk
- Missing:
  - Full calibration (ongoing work on multi-period extension and validation/ calibration strategy)

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Related work

- *Giansante et al.* (2012): study of interactions between liquidity and solvency
  - Counterparty solvency and liquidity scoring index determining behaviors
- *Bookstaber et al.* (2017): towards Agent-based modelling (ABM) approach
  - Interacting players: liquidity demanders, suppliers, market makers
  - Endogenising liquidity supply fluctuations (cyclical with periods of crises)
- *Riedler et al.* (2016): Evaluating financial regulation
  - Comprehensive list of agent types that played a role during the 2008 crisis
- *Calimani et al.* (2017): Fire-sales in banking and shadow banking system
  - Role of business models in fueling fire-sales
- *Montagna & Kok* (2013); *Halaj & Kok* (2014); Lux (2015); Liu et al. (2018)…
  - Interbank formation
- ECB/ Bank of England/ Oxford Univ./ UCTown/OFR…: initiatives to build a framework

ABM framework – model set-up

based on Hałaj (2018) and extensions with M. Gątkowski

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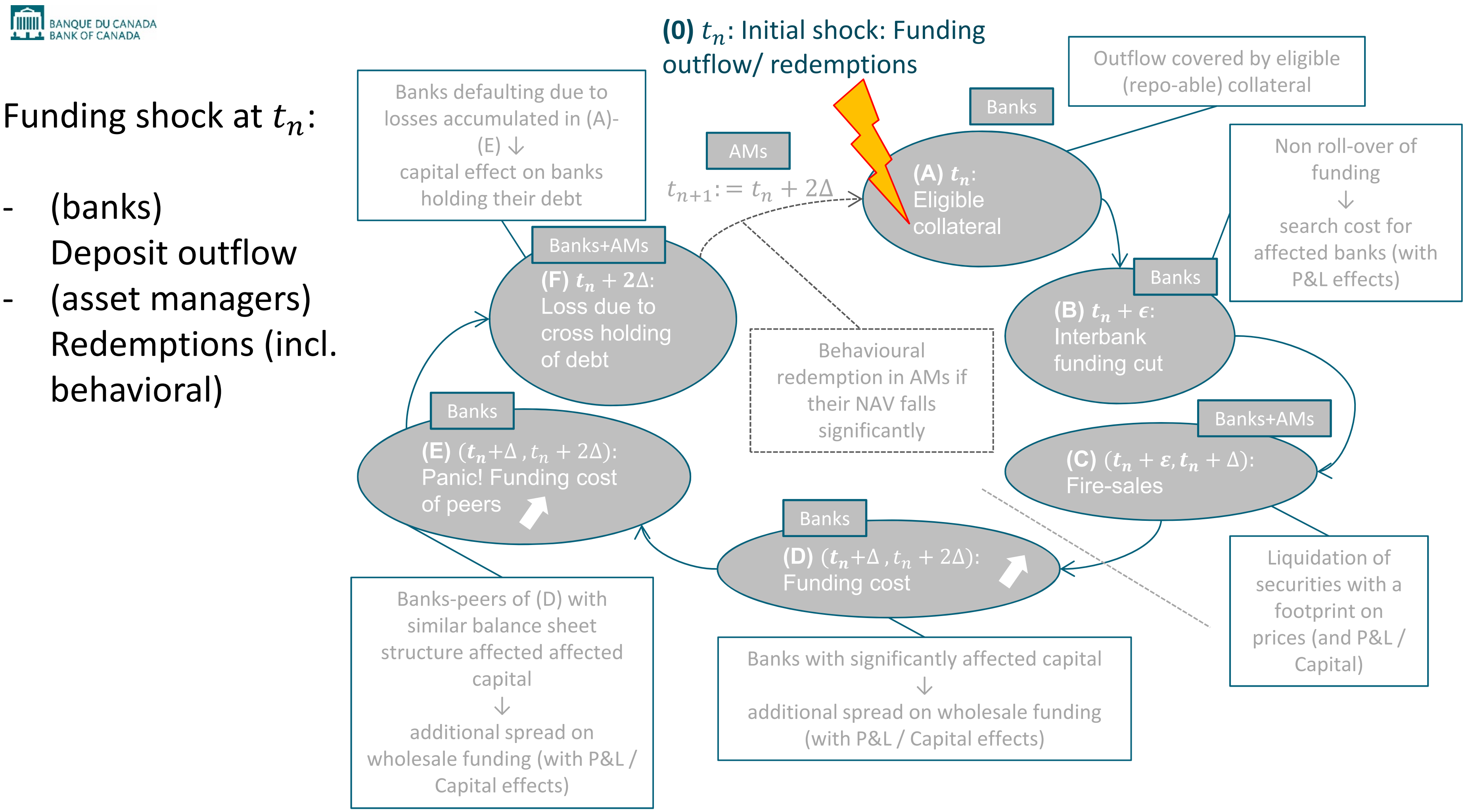
Model basics

- Objective of agents: withstand a liquidity/ funding shock based on set of predefined behavioral rules
  - Mechanistic rules, no optimisation
- Multi-layer setup – consistent with liquidity risk channels:
  - Interbank lending: broken lending relationship
  - Asset commonality: fire sales
  - Business models: indirect (information) contagion
  - Cross-holding of bank debt: bond defaults
- Following the shock, events in sequence:
  - Immediate liquidity buffers (e.g. $\varepsilon = 1$day): usage of eligible collateral + intertbank
  - Less liquid buffers (e.g. $\Delta = 1$month): fire-sales,
  - Longer term consequence (2Δ): funding costs + defaults

Funding shock at t_n:

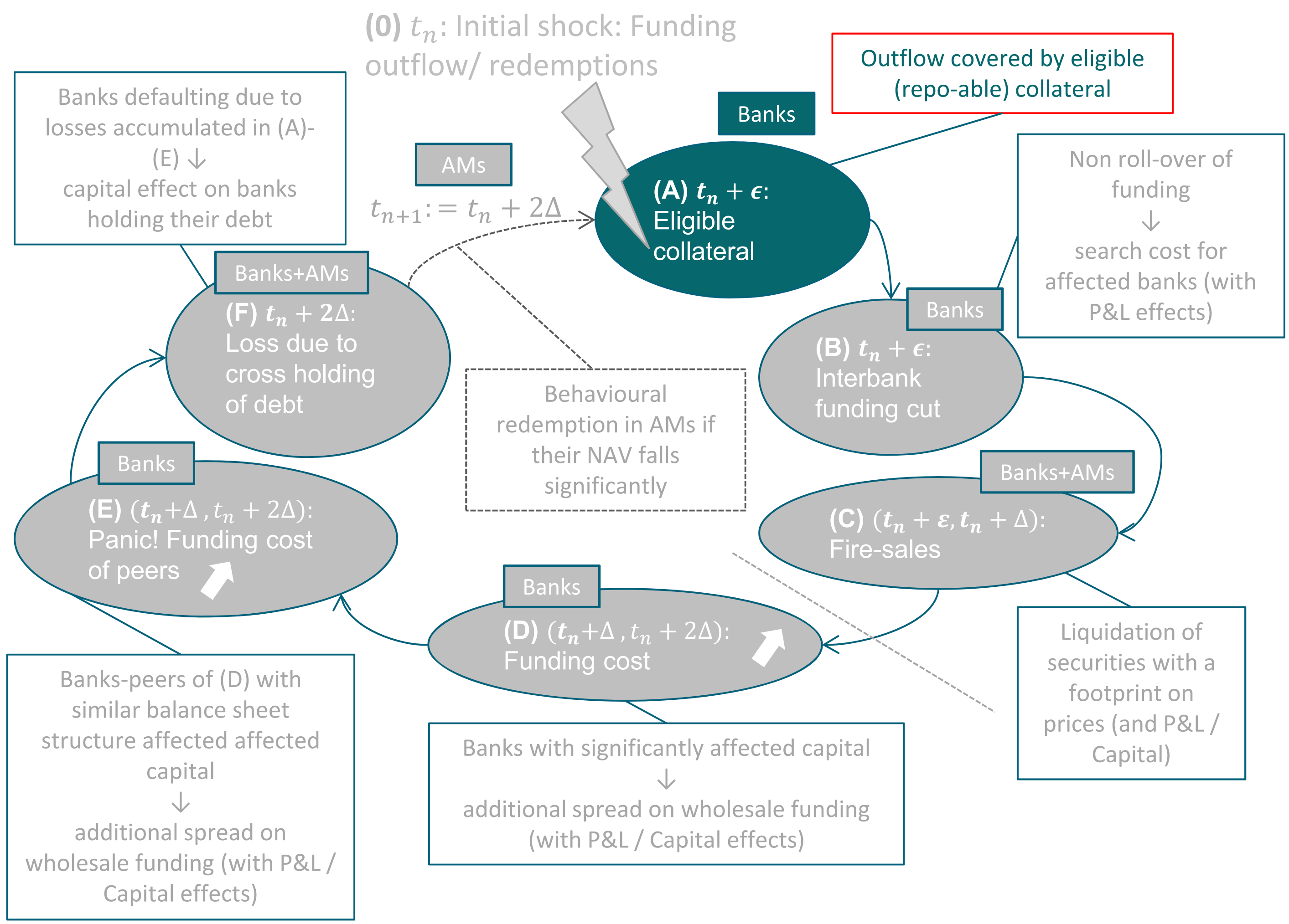
- (banks) Deposit outflow
- (asset managers) Redemptions (incl. behavioral)



At time $t_n + \varepsilon$:
(ε = 1day)

Usage of (liquid) eligible assets to cover the shock

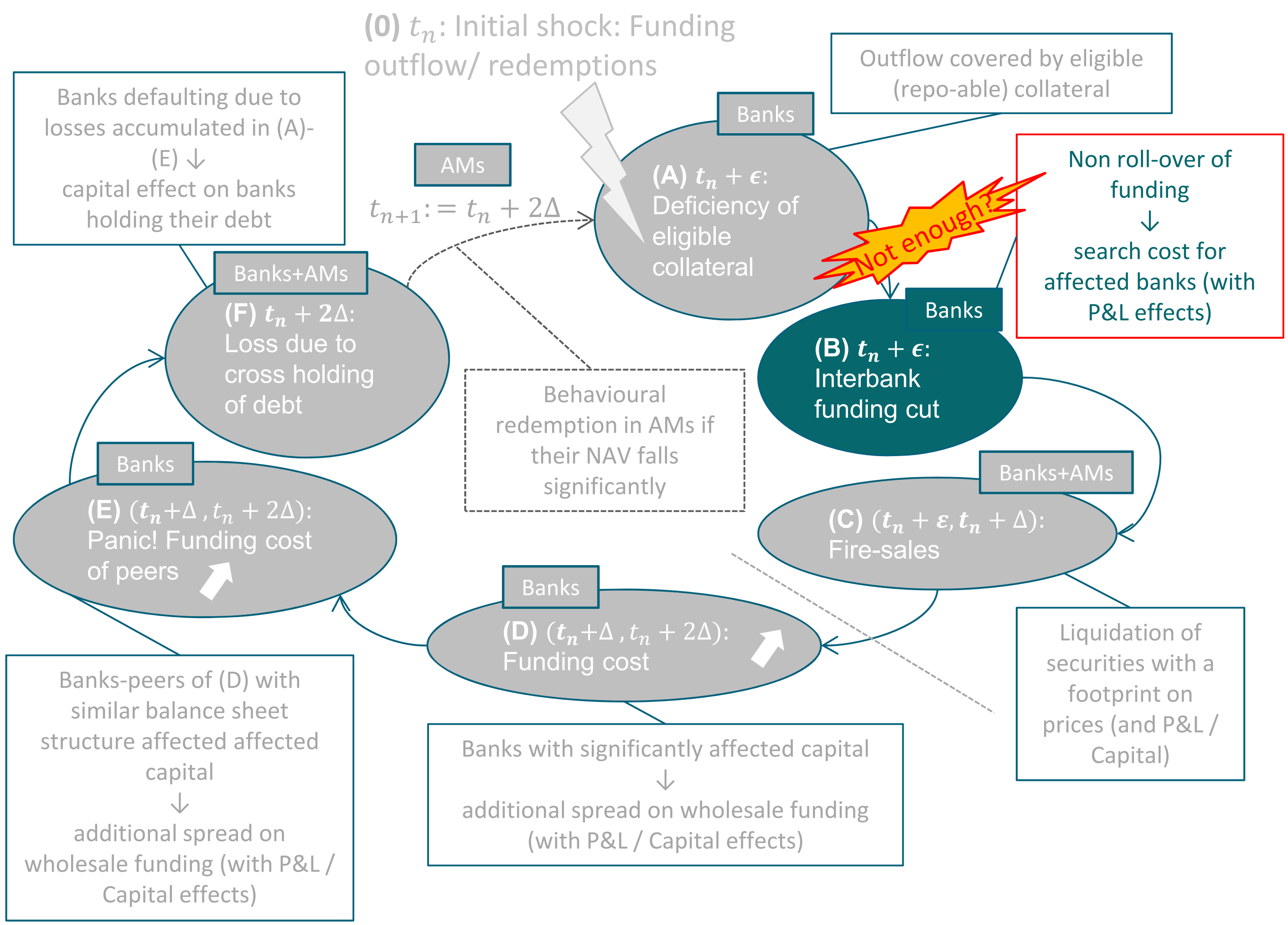
If insufficient…



At time $t_n + \varepsilon$:

…then interbank funding lines cut

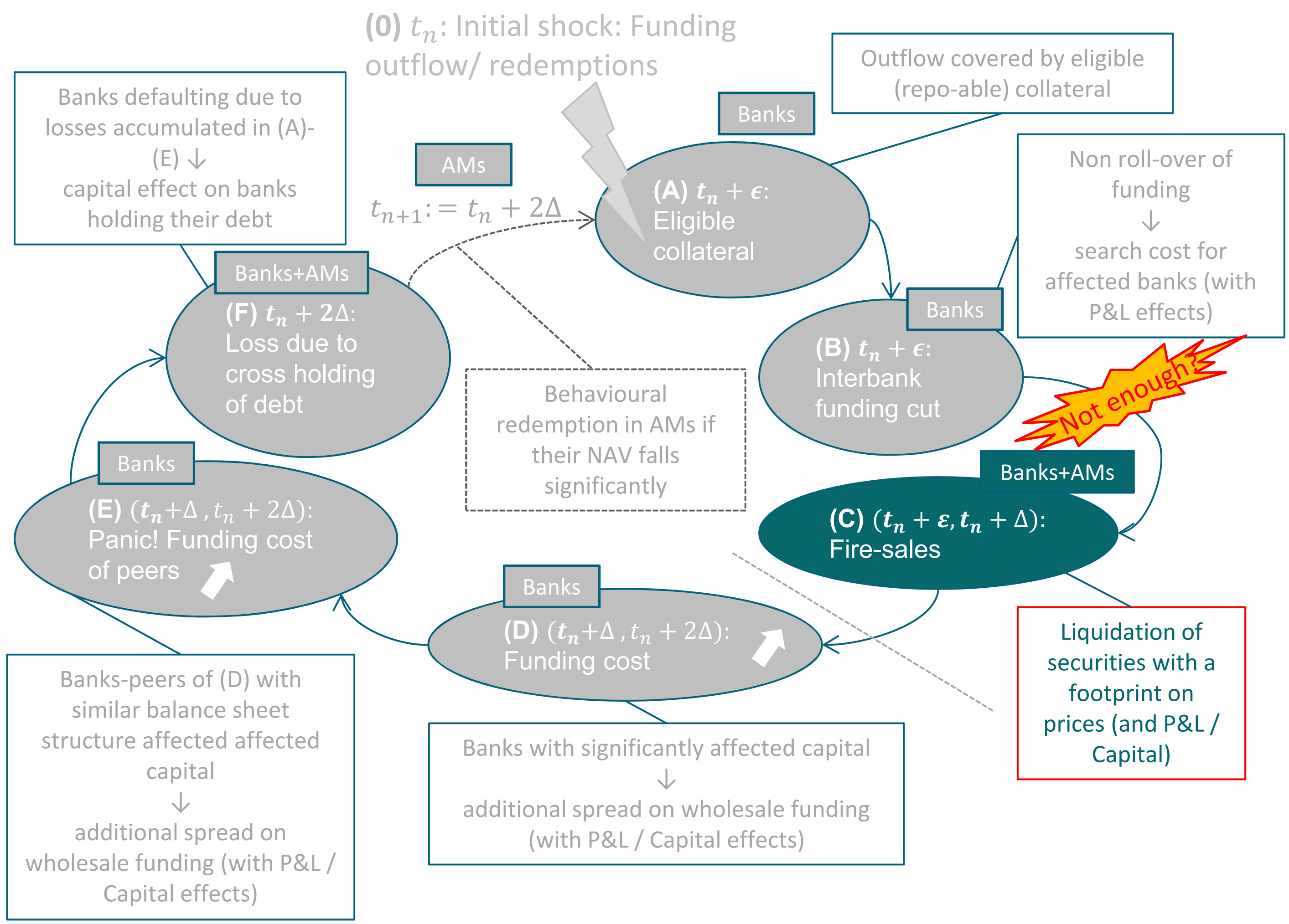
But if insufficient…



In period
$(t_n+\varepsilon, t_n + \Delta)$:
(Δ = 1month)

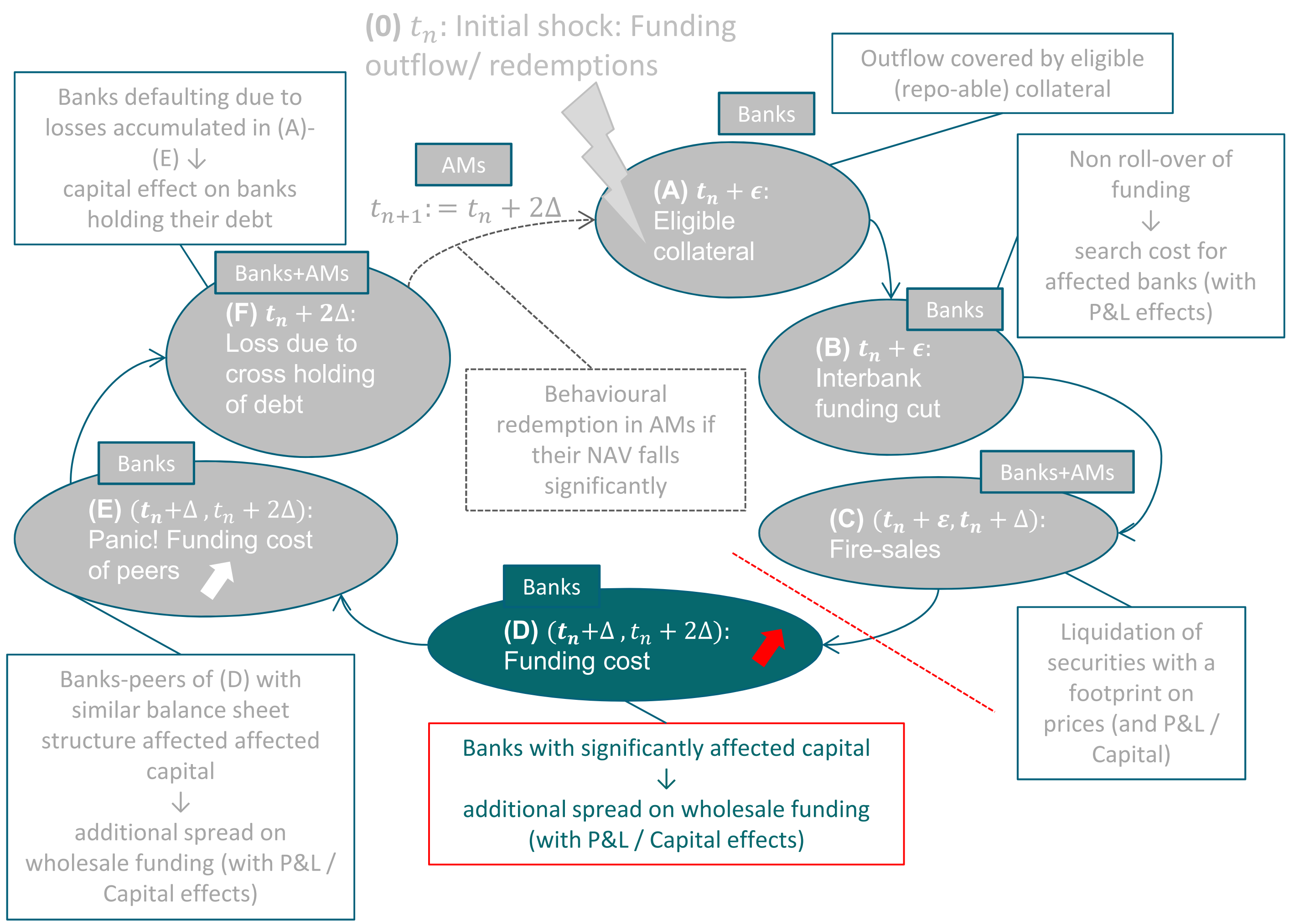
… fire sales of less liquid assets

Market-wide price impact → MtM revaluation of banks' and AMs' assets



In period
$(t_n+\Delta, t_n + 2\Delta)$:

Losses impact banks capital ratios → funding cost spread



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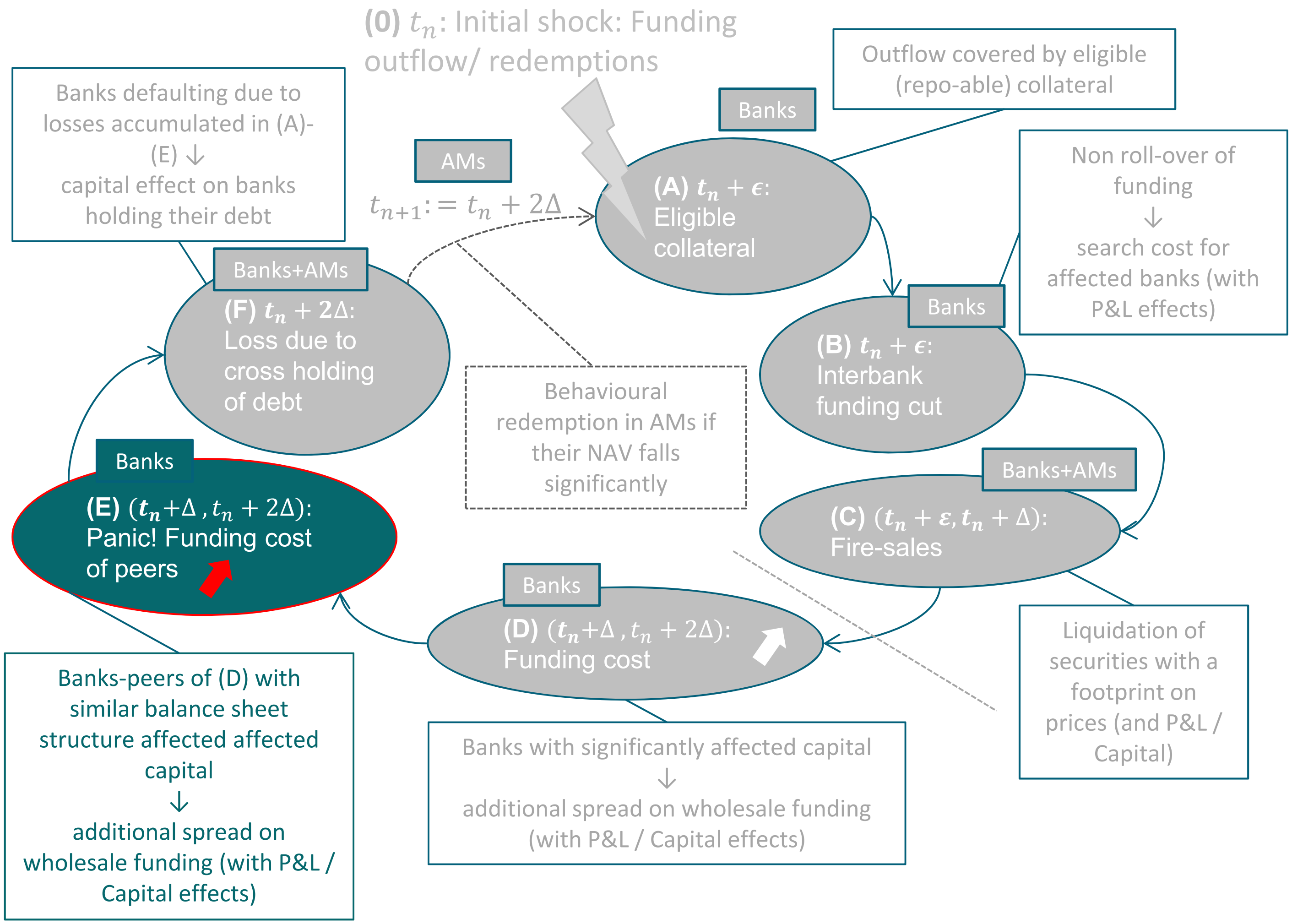
In period $(t_n+\Delta, t_n+2\Delta)$:

Peers of banks affected on funding market (indirect contagion channel) → funding spread



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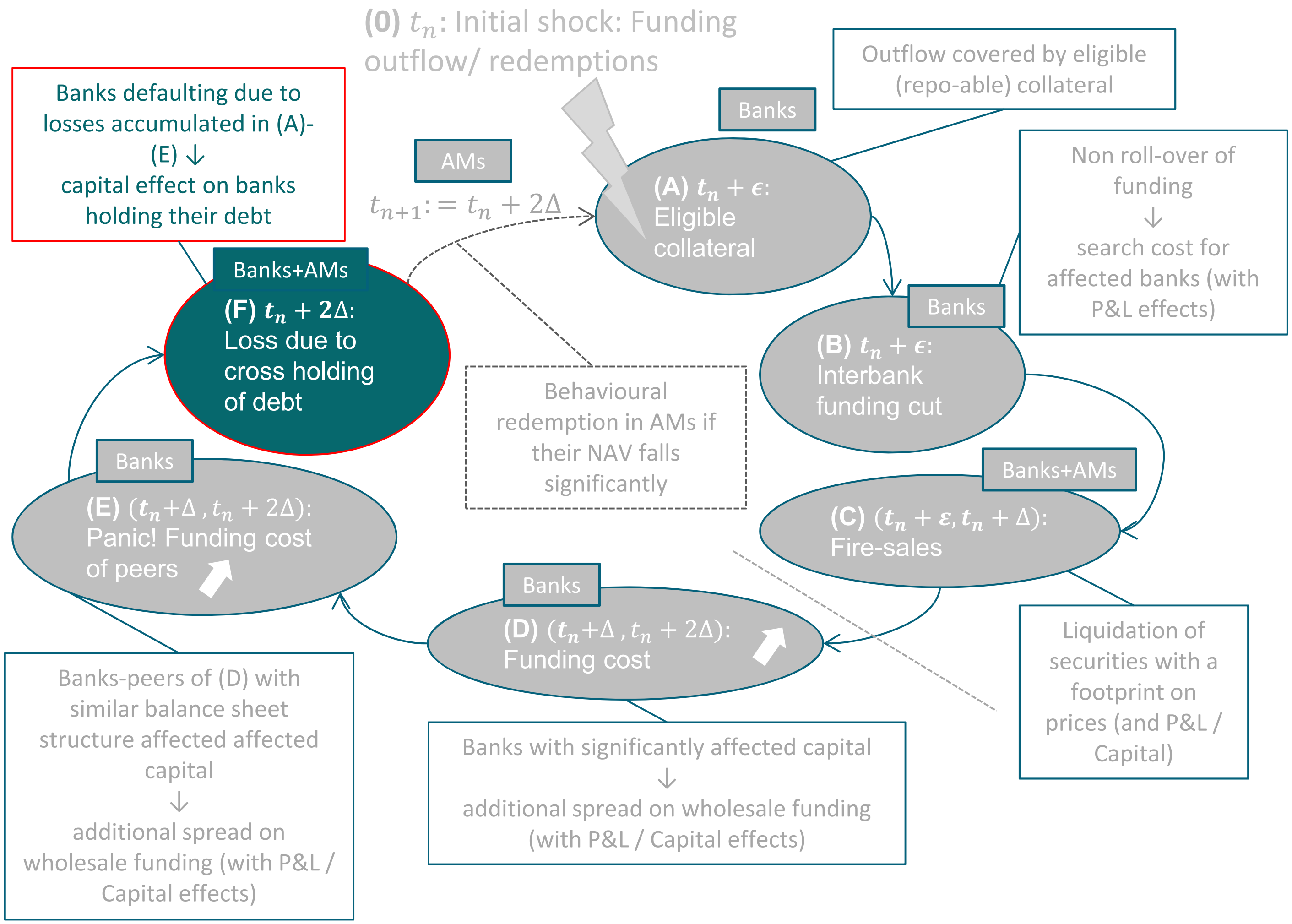
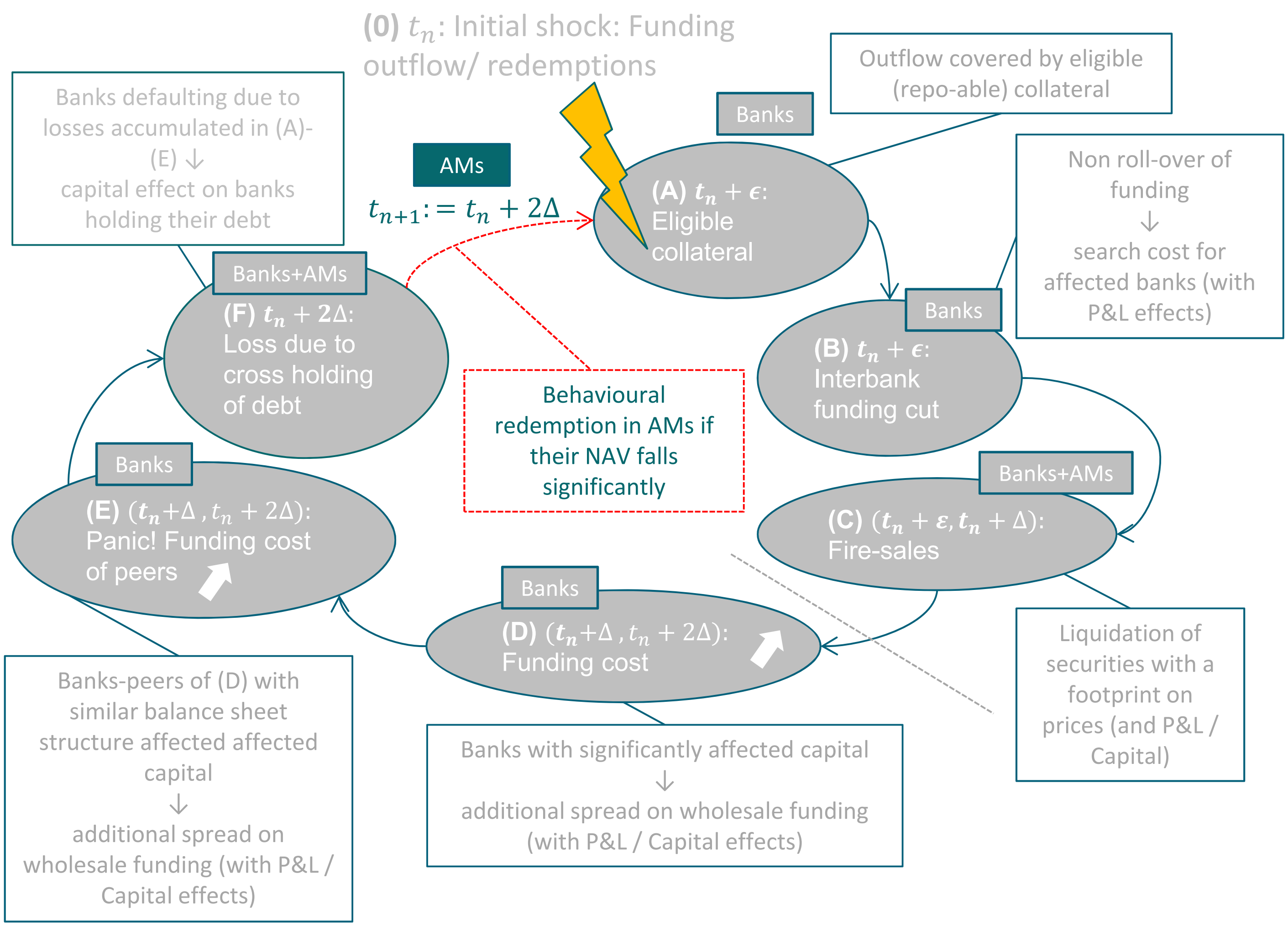
At time $t_n + 2\Delta$:

Defaults in case of capital ratios falling below regulatory minimum
→ direct contagion channel via cross-holding of debt instruments issued by banks



At time $t_n + 2\Delta$:

Behavioral redemptions experienced by AMs with a slump of their market value → additional funding shock triggering step (A) in t_{n+1} and amplifying contagion losses



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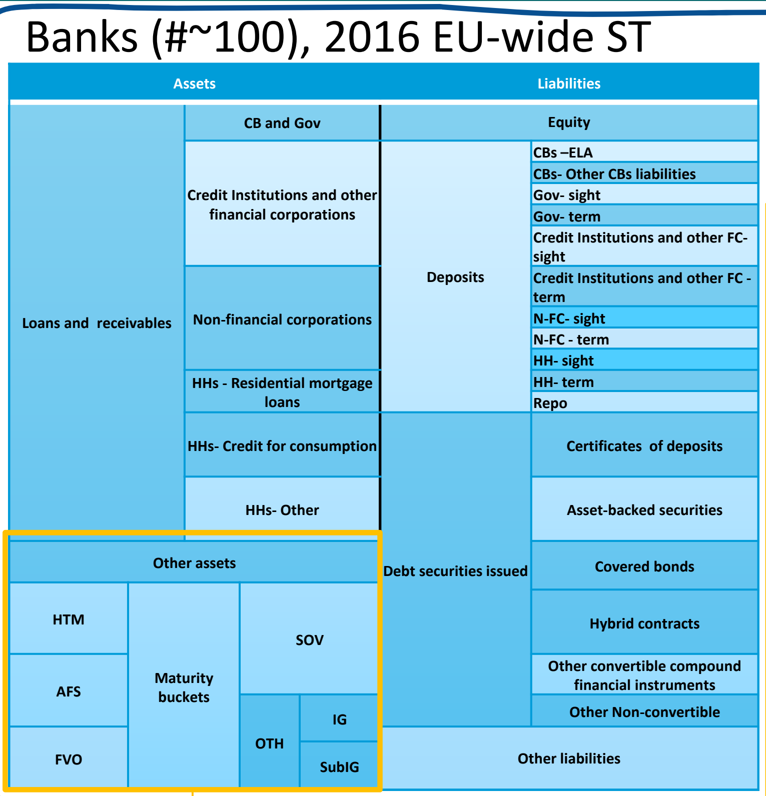
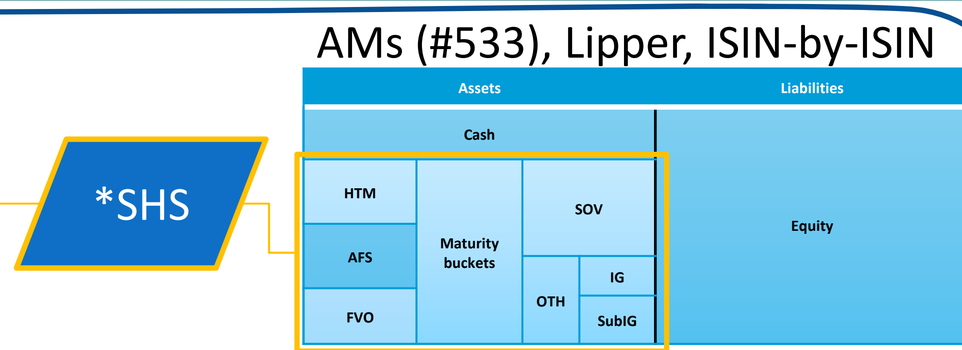
Parametrisation: data-intensity of the model





Constraints:
- *Liquidity (LCR)*
- *Capital*

For most of the assets and liabilities information on originating country or currency ≈ 10000 rows of data

*) SHS – securities holding statistics (ISIN by ISIN for 26 EU banks)

Exposures of banks and AMs – heterogenous and cross-border

Total mln €	Domicile	AT	BE	CY	CZ	DE	DK	ES	FI	FR	GB	IE	IT	LU	MT	NL	NO	PL	PT	RO	SI	SK	US	CH	RoEEA	RoW
91,475	AT	25%	2%	0%	10%	5%	0%	6%	1%	7%	1%	1%	8%	0%	0%	2%	0%	5%	1%	6%	1%	8%	2%	0%	6%	3%
82,027	BE	2%	31%	0%	10%	3%	0%	8%	0%	12%	2%	2%	14%	0%	0%	3%	0%	1%	0%	0%	0%	3%	6%	0%	3%	1%
1,657	CY	0%	2%	64%	0%	4%	0%	0%	0%	18%	2%	2%	1%	0%	0%	1%	0%	0%	0%	0%	0%	0%	6%	0%	0%	0%
441,762	DE	1%	2%	0%	0%	56%	1%	5%	1%	5%	2%	1%	8%	1%	0%	3%	0%	2%	1%	0%	0%	0%	5%	0%	2%	4%
6,666	DK	0%	0%	0%	0%	3%	79%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	17%
294,053	ES	0%	0%	0%	0%	0%	0%	62%	0%	1%	3%	0%	7%	0%	0%	0%	0%	2%	6%	0%	0%	0%	5%	0%	0%	14%
29,872	FI	1%	3%	0%	0%	24%	0%	13%	1%	14%	0%	2%	23%	0%	0%	11%	0%	0%	2%	0%	0%	0%	0%	0%	5%	0%
413,801	FR	2%	8%	0%	1%	8%	0%	7%	1%	38%	2%	1%	15%	0%	0%	3%	0%	1%	1%	0%	0%	0%	6%	0%	0%	6%
361,284	GB	0%	0%	0%	0%	0%	0%	0%	0%	0%	97%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	2%
201,467	IE	1%	1%	0%	0%	12%	0%	11%	0%	14%	32%	9%	18%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
385,105	IT	2%	1%	0%	1%	8%	0%	8%	0%	3%	0%	0%	68%	0%	0%	0%	0%	1%	1%	1%	0%	1%	1%	0%	2%	2%
282,186	LU	2%	6%	0%	0%	29%	0%	11%	0%	17%	2%	2%	20%	0%	0%	4%	0%	0%	1%	0%	0%	0%	1%	0%	2%	1%
1,345	MT	1%	0%	0%	0%	10%	0%	2%	3%	4%	0%	0%	1%	0%	61%	6%	3%	1%	0%	0%	0%	0%	0%	0%	2%	5%
253,677	NL	4%	9%	0%	0%	19%	0%	5%	3%	17%	0%	1%	6%	0%	0%	21%	0%	2%	0%	0%	0%	0%	3%	0%	1%	6%
15,495	NO	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	99%	0%	0%	0%	0%	0%	0%	0%	0%	0%
23,279	PT	0%	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%	5%	0%	0%	0%	0%	10%	61%	0%	0%	0%	1%	0%	0%	22%
2,947	SI	5%	4%	0%	1%	4%	0%	1%	2%	5%	0%	0%	2%	1%	0%	4%	0%	1%	0%	0%	57%	1%	0%	0%	1%	12%
8,416	CH	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	93%	0%	3%
14,832	SE	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	97%	0%
1,556	LV	0%	0%	0%	0%	1%	1%	0%	2%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	63%	0%	24%	5%
1,371	LI	0%	4%	0%	0%	8%	4%	0%	0%	12%	10%	2%	0%	0%	0%	3%	0%	2%	0%	0%	0%	0%	41%	0%	0%	15%
2,914,273	**Total**	**2%**	**4%**	**0%**	**1%**	**16%**	**0%**	**12%**	**1%**	**12%**	**15%**	**1%**	**18%**	**0%**	**0%**	**3%**	**1%**	**1%**	**2%**	**0%**	**0%**	**1%**	**3%**	**0%**	**2%**	**4%**

Notes: Exposure of agents domiciled in country XX (column) to assets with origination in country YY (row) (as % of total exposure)

Sensitivity analysis and simulations

Multiperiod set-up: rolling over 6-step sequences

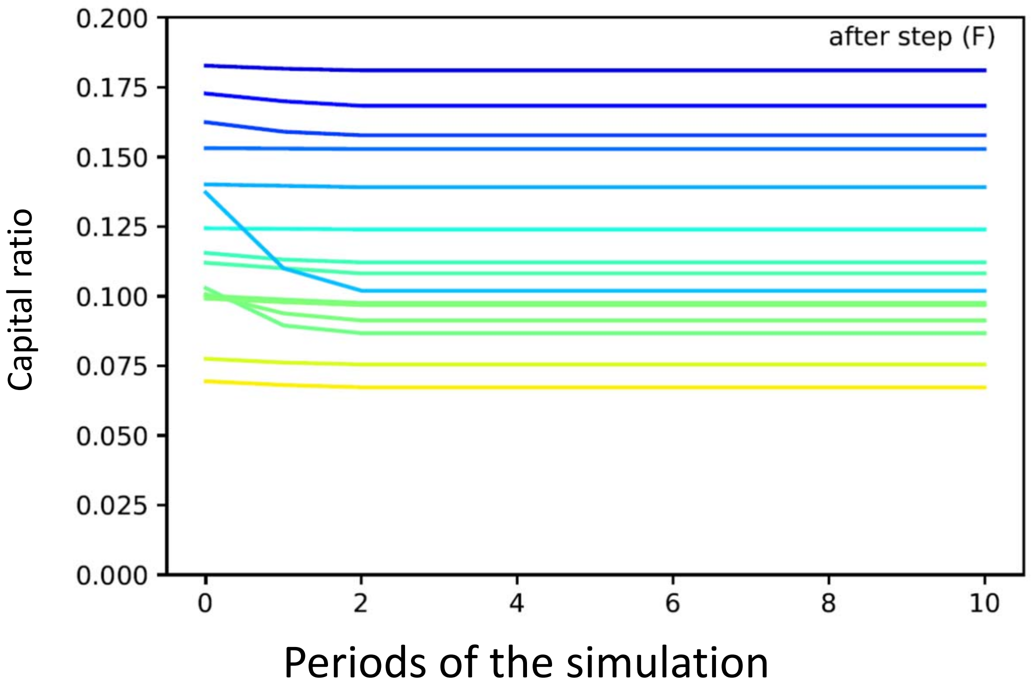
- End of period *t* becomes the initial structure at *t+1*
- What needs to be taken care of:

	Simplified approach	Comprehensive approach
A	no modification *implicitly, short-term shock and liquid volumes are rebuilt in (t,t+1]*	fraction (random?) of liquid volumes rebuilt *persistence of shock*
B	rewiring of interbank links *links from banks cutting lending disappear*	rewiring of interbank links *links disappear and new (from creditors) are formed*
C	prices recovery *immediately*	partial recovery of prices *liquidate volumes aggregated for s<t*
D	funding costs recovery	partial recovery of funding costs *persistance of the elevated funding spreads*
E	funding costs recovery	partial recovery of funding costs *persistance of the elevated funding spreads*
F	defaulted banks disappear from the model *contracting system*	replacements of the defaulting banks *newborns with a given intensity in time*

- So far, no investment strategy to drive the evolution of balance sheets

‘Impulse response’ of the system

- Outflow shock at t=0 to a random sample of banks
- Results:
  - Heterogenous responses
  - Impact of the shock dies out after 3 periods



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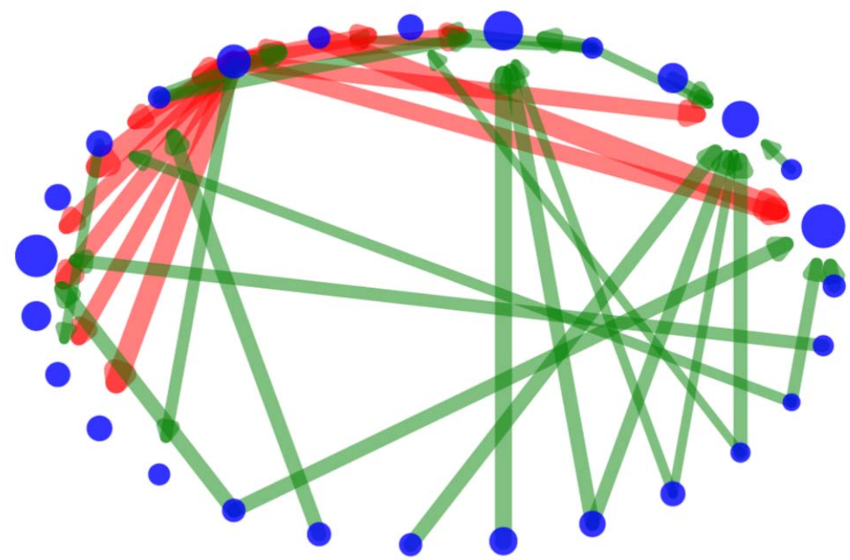
Zoom in: step B and dynamic rewiring of interbank

- The same exercise as on previous slide
- Banks affected by cutting of interbank lending search for other sources → matching with banks with liquidity surplus
- Result: (complex) changes in the topology

Affected interbank linkages



Red: links cut in step B;
Green: links formed by affected banks

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Conclusions

- Agents built (parameterised) and interactions (channels) specified…
- but (full) calibration missing
- Success in policy application depending on
  - data availability to properly reflect features of the agents
  - appropriate validation strategy
  - integration of behaviours in such a way that the sensitivities in the model can be intuitively explained
  - link with general financial market and real economy trends (exogenous to the model)

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Appendix

Appendix 1: Why ABM approach?

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ABMs are particularly useful to study complexity of financial system

- Main difficulty with the modelling of financial system:
  1. *Granularity: continuum is not a good approximation of the set of exiting banks*
  2. *Cardinality: the minimal number of parameters needed to describe agents is large*
- Ad. 1: only ≈100 banks in Europe, 6+ in Canada …
- Ad. 2: …but heterogenous in BS composition, market penetration, local market practices and legal specificities → how to aggree on a small set of unified assumptions describing this system? How to test them?
- Protagonists of ABMs say: equilibrium should emerge, should not be imposed in a model since it is too heavy assumption bringing an unnecessary rigidity to the models (*Sinitskaya & Tesfatsion* , 2015).

- Difficulty with ABMs: how to interpret results, how to detect drivers of the results?

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Building blocks of ABMs (after *Fagiolo & Roventini*, 2017)

- Bottom-up perspective: micro outcomes aggregate to the macro
- Heterogeneity: in all aspects
- Evolving complex systems: properties of the system emerge from agents' interactions rather than consistency/ equilibrium imposed *ex ante*
- Non-linearity: feedback loops between aggregate and micro level
- Direct interactions: decisions depend on the past choices of other agents
- Bounded rationality + learning: local principles, myopic rules, adaptation
- Persistent novelty: new patterns of behaviors, also endogenous
- Selection-based markets: goods/ services are selected based on complex rules

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Appendix 2: Flow-charts

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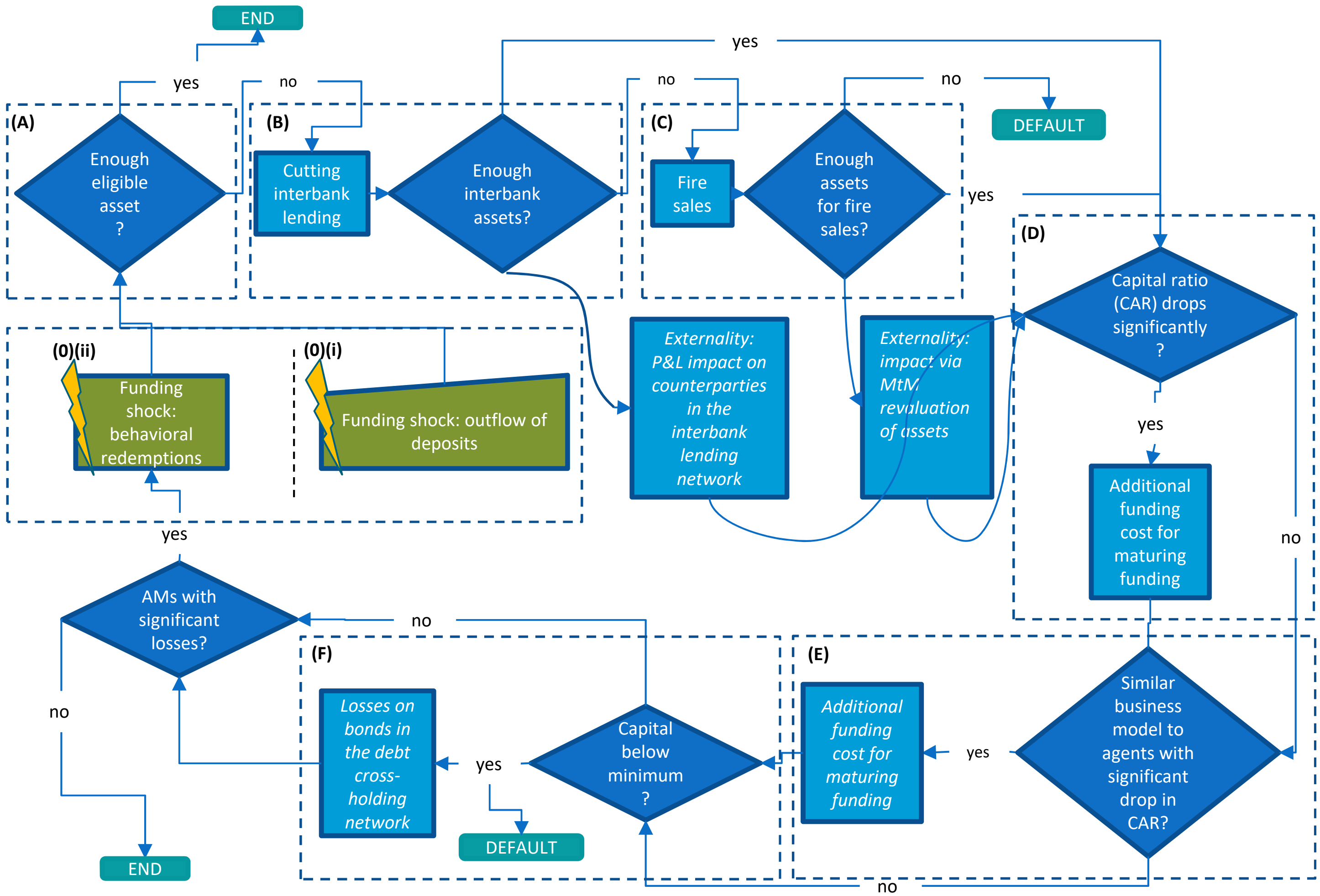
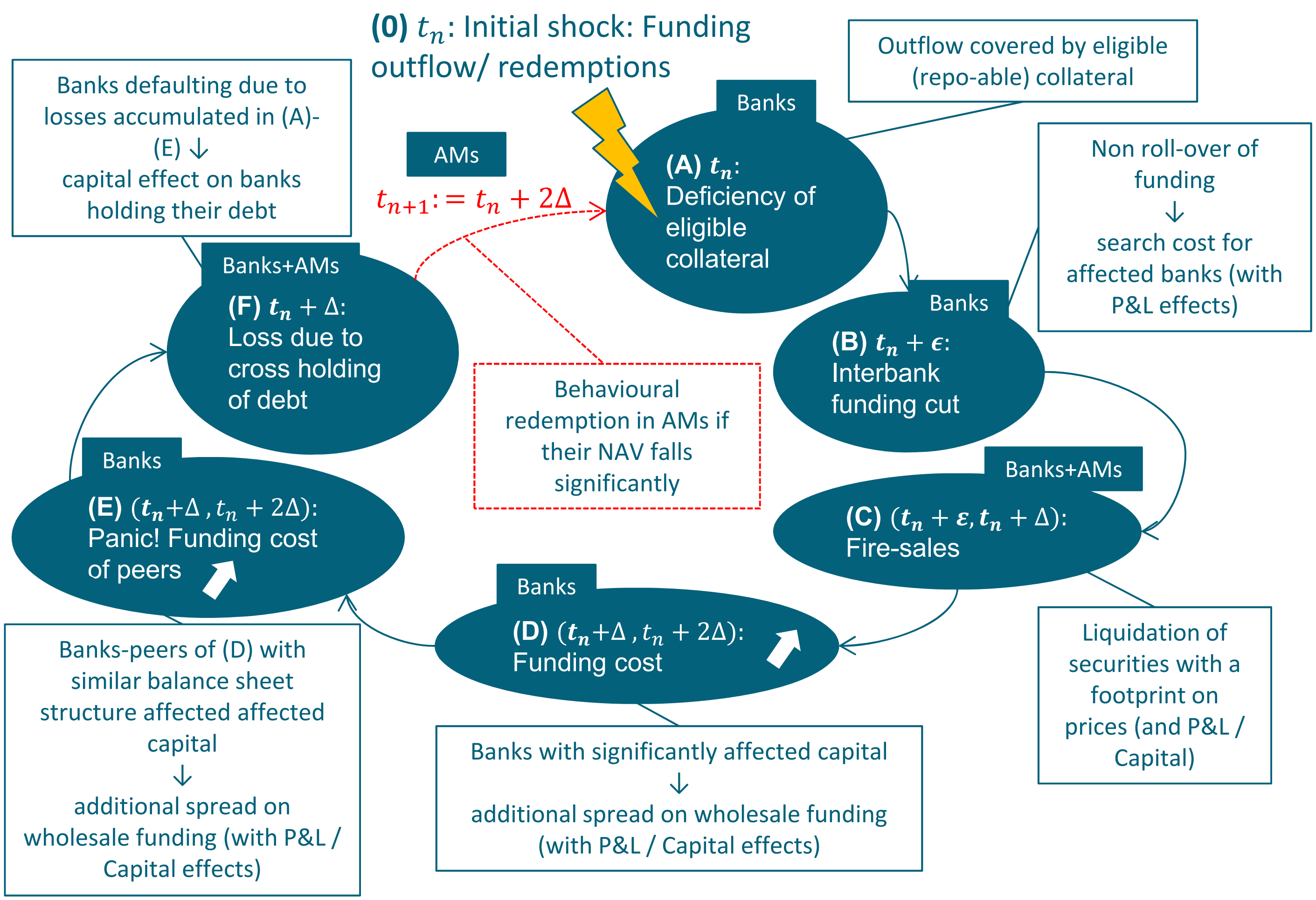
- Objective of agents: withstand a liquidity/ funding shock based on a set of predefinced rules
- Multi-layer setup:
  - *i.* *Interbank lending: broken lending relationship*
  - *ii.* *Asset comonality: fire sales*
  - *iii.* *Business models: funding cost spill-overs*
  - *iv.* *Cross-holding of bank debt: bond defaults*



- Mechanistic rules, no optimisation
- Objective of agents: withstand a liquidity/ funding shock based on a set of predefinced rules
- Multi-layer setup:
  - *i. Interbank lending: broken lending relationship*
  - *ii. Asset comonality: fire sales*
  - *iii. Business models: funding cost spill-overs*
  - *iv. Cross-holding of bank debt: bond defaults*
- Example: ε = 1day; Δ = 1month



Appendix 3: Further work – full validation

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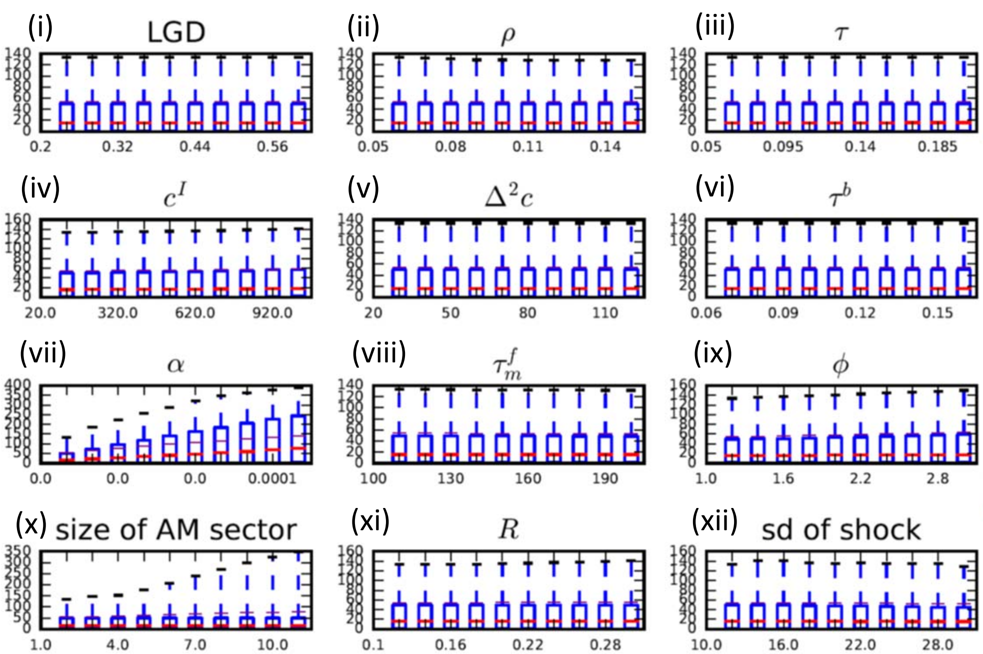
Sensitivity of contagion ΔCAR to key parameters – one-by-one

- Parameters: (*i*) loss-given default; (*ii*) redemption threshold; (*iii*) similarity of business models; (*iv*) interbank search cost; (*v*) funding cost spread for peers; (*vi*) insolvency threshold; (*vii*) price elasticity in fire-sales; (*viii*) funding cost threshold; (*ix*) elasticity of funding costs; (*x*) AM relative size; (*xi*) redemption rate; (*xii*) standard deviation (sd) of the initial shock
- Draw randomly a group of banks and size of the shock and produce the CAR impact
- Construct a distribution of ΔCAR (in bps)



6-step chain played twice to capture AM-bank feedback

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Sensitivity of contagion ΔCAR to key parameters – panel regression

- Selecting a set of parameters and ranges of their values
- Sampling vectors of parameters from a uniform distribution (very expensive → better methods available: importance sampling, tessellation, orthogonal Latin hypercubes,…)
- Running the 6-step model (two sequences)
- Collection ΔCAR for each bank
- Running panel regression

	Dependent variable: Capital Adequacy Ratio (pooling)	(within)
Loss given default	0.025684**	0.026030**
	(*2.105130*)	(*2.367974*)
Behavioral redemption threshold	0.031816	0.032467
	(*0.486583*)	(*0.551136*)
Bank similarity threshold	−0.215172***	−0.215035***
	(*-7.442242*)	(*-8.255511*)
Interbank search cost (spread)	0.005583*	0.005578**
	(*1.906945*)	(*2.114496*)
Funding cost spread	−0.078644***	−0.078632***
	(*-13.019000*)	(*-14.448500*)
Capital threshold	0.156951	0.155356
	(*1.394320*)	(*1.531893*)
Price impact of fire-sales	−0.062310	−0.062702
	(*-1.065707*)	(*-1.190348*)
Funding cost insensitivity region	0.007644**	0.007748**
	(*2.006848*)	(*2.257796*)
Funding cost sensitivity to ΔCAR	−1.038174***	−1.016824***
	(*-2.629390*)	(*-2.857761*)
Relative size of AM sector	0.100601	0.098216*
	(*1.555868*)	(*1.685804*)
Behavioral redemption rate	0.015347	0.015647
	(*0.252789*)	(*0.286064*)

Control variables: capital ratio; share of non-liquid assets in total assets (TA); share of MtM assets in TA; share of eligible assets in TA; degree measure in interbank network; degree measure in cross-holding of debt network

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Levels of validation (*Barde & van der Hoog*, 2017)

- Level 0: the model is a caricature of reality, as established through the use of simple graphical devices (e.g., allowing visualization of agent motions).
- Level 1: the model is in qualitative agreement with empirical macro structures, as established by plotting e.g. the distributional properties of agent population. This is easiest way to matching stylized facts.
- Level 2: the model produces quantitative agreement with empirical macro-structures, as established through on-board statistical estimation routines.
- Level 3: the model exhibits quantitative agreement with empirical micro-structures, as determined from cross-sectional and longitudinal analysis of the agent population.

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Many ways seem to be available

- Analysing (estimating) emergent properties stemming from ABMs (*Alfarano et al.* 2005; *Lux*, 2012) and replication of stylised facts (time series dynamics)

or

- Exploring parameter space (*Salle & Yildizoglu*, 2013; *Bargigli et al.*, 2017) → Meta-modelling → Kriging (sometimes called 'spatial' estimator)

or

- Comparing causal structure in the data generated by the model and the real world: VAR

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Kriging (application by *Dosi et al.*, 2017)

- Sensitivity analysis: computationally costly to simulate models for a (sufficiently) large number of vectors of parameters → meta-model (perturbed deterministic function of a small number of parameters)

1. sampling: NOLH (filling in the parameters space with ϵ-orthogonal vectors)
2. building meta model: ABM approximated by linear combination on NOLH
    - Estimation part: correlation using ML
3. measuring sensitivity based on variance decomposition: Sobol decomposition
4. taking the 2 parameters that explain the variance the most: (graphical?)

If data are spatially inhomogeneous – selection of points for interpolation difficult:

→ Machine learning to learn Meta model (*Lamperti, Roventini & Sani*, 2018)

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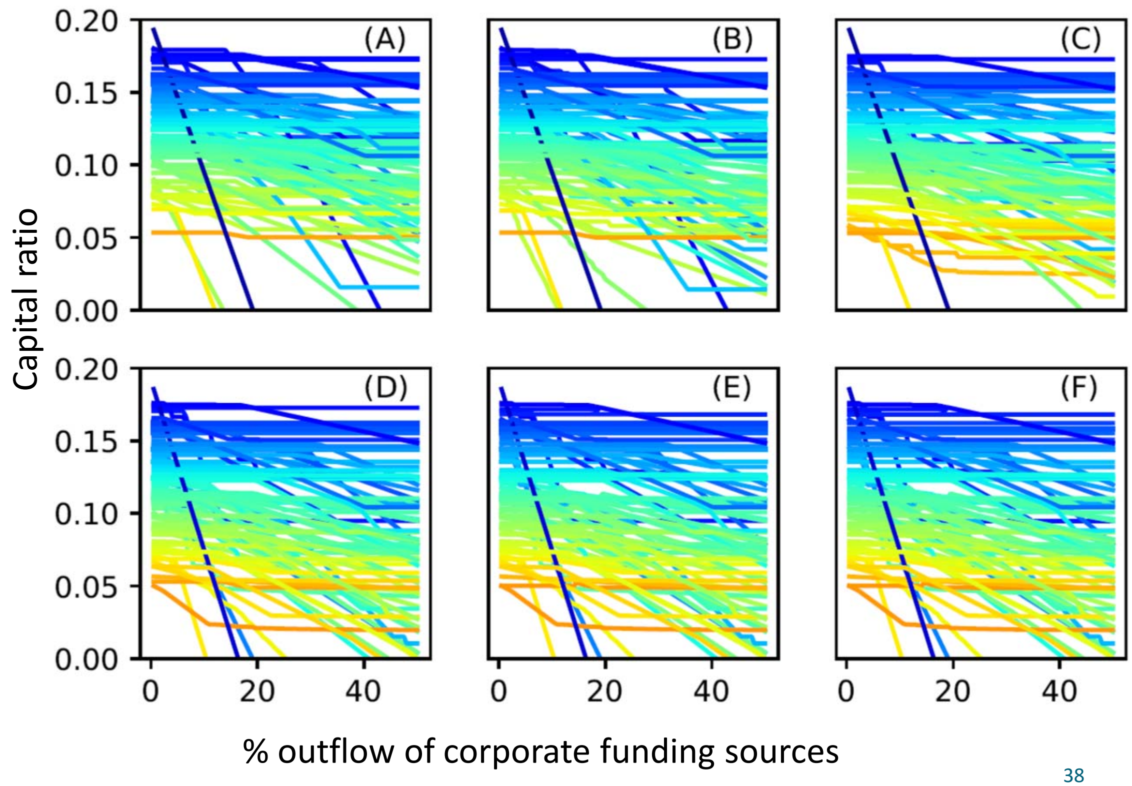
VAR – based method: validation based on causation

1. Data preparation (e.g. detrending)
2. Stationarity and ergodicity tests
3. VAR estimation (based on data obtained in 1.)
4. SVAR on real data (residuals from VAR are used to search for causal relationship)
5. Distance measures of the casual structures.

Simulation 1: how do losses depend on shock size?

- Scenario: random selection of funding lines and banks, and for a chosen funding outflow rate running the 6 step model
- Plotting bank individual CARs for each step
- Results:
  - *Lots of heterogeneity in responses*
  - *Cliff effects*



Simulation 2: How does contagion depend on the LCR requirements

- Scenario: random sample of banks hit by outflow shock for a given funding category
- Plotting average CAR reductions for each pair (funding category, domicile of hit banks)
- Results:
  - *Again, heterogeneity of sensitivity of contagion losses to the required level of unencumbered liquid assets after the shock*
  - *Policy assessment and risk monitoring tool*