Crisis, contagion and containment policies in financial networks : A dynamic approach

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1 Introduction

We wish to create a model of financial networks that can be used for any structure of network. Each node's state is given by a simplified balance sheet from which an equity can be computed. This is the quantity that determines whether a node is in default. We want to only consider solvency defaults and not liquidity default which cannot happen in our setting. We will then simulate the propagation of different types of shocks on this network in a dynamic fashion going one step further in comparison to the existing literature that uses either a fixed small number of periods ([**10**]) or a "killing cascade" as dynamics ([**1.1**], [**11**])—after an initial shock, banks may default, we check if those defaults bring about new defaults, and so on until no more banks are defaulting. Having a real time dynamics will open the way for the study of dynamic resource allocations strategy on the network to try to contain potential systemic events in the fashion of [**5.2**].

2 Economic description of the model

We focus our analysis on banks and the only type of credit we consider is inter-bank loans. Banks do not take stakes in one another. The outside economy is simply modelled as a set of risky assets which yields random returns, they could represent for instance loans to companies, to individuals, investment in public projects... as well as financial products.

2.1 Banks

2.1.1 Balance sheet representation

Let n be the number of banks in the network. At each time t, bank j is represented as a simplified balance sheet :

Assets ($\mathcal{A}_t^i$)	Liabilities ($\mathcal{L}_t^i$)
Reserve (R_t^i)	Equity (E_t^i)
Inter-bank loans (L_t^i)	Inter-bank debts (D_t^i)
Portfolio (P_t^i)	

- On the assets side :
  - Reserve R_t^i is the amount of reserves, a fraction or the totality of them may be kept in a central bank.
  - L_t^i corresponds to the cumulative face-value of loans going from bank i to other banks. Also, let us denote by L_t^{ij} the face-value of the loan going from bank i to j. Thus $L_t^i = \sum_{j=1}^n L_t^{ij}$
  - Portfolio P_t^j is the amount of money invested in the economy — more on that in section 2.2.
- On the liabilities side :
  - Equity E_t^i is equal to the assets minus the liabilities. Thus it is when equity goes under 0 that a bank is said to go bankrupt.
  - D_t^i corresponds to the cumulative face-value of the loans coming from other banks to bank i. Thus $D_t^i = \sum_{k=1}^n L_t^{ki}$.

Let us denote by :

- $L_t \in \mathcal{M}_{n,n}(\mathbb{R}^+)$ the matrix of inter-bank loans which entries are the L_t^{ij}. Two important remarks :
  - In order to simplify the graph as much as possible, loans and debts will be netted, which means that $L_t^{ij} > 0 \Rightarrow L_t^{ji} = 0$. Given a matrix L_t, we can obtain its netted version L_t' using component-wise maximum by doing the following operation :

    $$L_t' = \max(\mathbf{0}_{n,n}, L_t - L_t^T)$$

    Where $\mathbf{0}_{n,n} \in \mathcal{M}_{n,n}(\mathbb{R})$ is the matrix full of zeros.
  - The matrix L_t contains all the information on the graph at time t, thus no need to have a debt matrix since it is simply equal to L_t^T, the transposed version of L_t.
- $E_t \in \mathcal{M}_{n,1}(\mathbb{R})$ the vector of equities which i-th element is E_t^i
- $R_t \in \mathcal{M}_{n,1}(\mathbb{R})$ the vector of reserves which i-th element is R_t^i

*Remark : the matrix L_t captures the structure of the graph. We will consider it given at first. In the simulation stages, we may test different random graph initialization as done in [**11**]*

2.1.2 Interest rates

We introduce the inter-bank interest rate r_t^i which determines the cost of borrowing for bank i at time t. Its existence is justified by the extra risk taken when lending money. We make several assumptions for now which we may relax later :

- Interest rates are deterministic
- r_t^j does not depend on time, thus we will omit the time-index $r_t^i = r^i$
- $\forall i \in [\![1, n]\!], \quad r^i = r$, thus every bank can borrow money for the same interest rate r to other banks.

2.2 Portfolios and investment opportunities

2.2.1 Risky assets

There are m risky assets in the economy. We take a wide definition of risky assets which entails productive investments such as loans to companies or individuals, investments in public projects... Thus risky assets are not necessarily stocks or financial products although they can be. The only fundamental conditions an asset need to match the definition are :

- to be outside of the network of banks
- to be risky to some extent

Each risky assets has a time-dependant valuation. For a given $l \in [\![1, m]\!]$, let us denote by X_t^l this price. Our model is in discrete time.

For now, those investments do not yield dividend. As a consequence gains (resp. losses) only come from increases (resp. drops) in the valuations.

We model the movements in prices using gaussian increases :

$$X_t^l = X_{t-1}^l + \omega_{t-1}^l$$

We model them using independent Gaussian random variables.

$$\omega_{t-1}^l \sim \mathcal{N}(\mu_l, \sigma_l^2)$$

We denote by ω_t the vector of increases. Since its components are Gaussian and independent, this is a Gaussian vector with :

- Mean vector $\mu \in \mathcal{M}_{m,1}(\mathbb{R})$
- Covariance matrix $\Sigma = Diag[(\sigma_l^2)_{1 \leq l \leq m}] \in \mathcal{M}_{m,m}(\mathbb{R}^+)$.

$$\omega_{t-1} \sim \mathcal{N}(\mu, \Sigma)$$

We make the assumptions that increases are independents across time :

$$\forall t \neq t', \; w_{t-1} \perp\!\!\!\perp w_{t-1'}$$

2.2.2 Bank's portfolios and valuation

Banks invest in those risky assets. Let us denote by $Q_t^i \in \mathcal{M}_{1,m}(\mathbb{R}^+)$ the vector which entry Q_t^{il} is number of unit of product l that bank i has in its portfolio at time t. The matrix $Q_t \in \mathcal{M}_{n,m}(\mathbb{R}^+)$ is the matrix which rows are the $(Q_t^i)_{1\leq j\leq n}$.

As a consequence, the value of i's portfolio is given by : $P_t^i = Q_t^i X_t$. The latter can be written in matrix form : $P_t = Q_t X_t$, with $P_t \in \mathcal{M}_{n,1}(\mathbb{R}^+)$ being the portfolio vector.

3 General dynamics of the system

3.1 Sequence of events

In this subsection, we establish the chronology of events without giving the equations. Since several operations take place within a given time-lapse t the ordering of events need to be precised. The detailed equations will be detailed later—at each stage a reference points to the appropriate section/subsection.

- **Stage 1 : updates** (detailed in 3.3). At the beginning of this stage, the state of a bank is given by the vector $(E_{t-1}^i, D_{t-1}^i, R_{t-1}^i, P_{t-1}^i, L_{t-1}^i)$. The following operations are then carried out

  - If banks have defaulted in the previous periods, the default is now effective and the creditors of the defaulted banks take the corresponding losses.
  - The reserves are updated: banks pay interest rates on inter-bank loans and if banks have defaulted in the previous periods, proceedings from liquidation are added to reserves.
  - The valuation of the risky assets are updated and the value of portfolios are changed accordingly.

  At the end of this stage, the state of a bank is given by a vector of five variables : $(\widehat{E}_t^i, \widehat{D}_t^i, \widehat{R}_t^i, \widehat{P}_t^i, \widehat{L}_t^i)$.

- **Stage 2 : checking for default**. Banks for which $\widehat{E}_t^i \leq \bar{E}^i$ declare default and are liquidated (see section 4 for the detailed processes of liquidation). Although their defaulting is not public information yet, it will become so at the beginning of the next period. The vector $\bar{E}$ which components are the $\bar{E}^i$ is a minimal threshold value for the equity of each bank. It enables us to implicitly include deposits from investors or individuals from outside the system in the balance sheets of the banks.

- **Stage 3 : balance sheet management** (detailed in 3.4) Banks readjust between portfolio and reserves according to (detailed in 3.2):

– The reserves rule

– The financial choice for the portfolio

At the end of the stage, the state of a bank is given by the 5 state variables $(E_t^i, D_t^i, R_t^i, P_t^i, L_t^i)$

3.2 Viability conditions

We need to introduce additional hypothesis, initial conditions and constraints in order to maintain our model's coherence.

- We assume that banks cannot have a negative expected variation of equity. Even though they are unidentified and not included in our model, we can assume that there are shareholders who own the banks. They indeed want their shares to gain value which justify our hypothesis on the variation of equity. This is the subject of section 3.2.1.
- If some banks have borrowed more than they have lent so as to invest in their portfolio section, their reserves will deplete mechanically after a given number of periods. As a consequence, we need to define transfer rules between portfolio and reserves. We thus introduce the reserve rule and the financial choice in 3.2.2.
- We make the assumption that banks can sell freely assets from their portfolio as a regular operation of management without paying any fees or having any price impact. This seems to be a reasonable hypothesis since only small amounts of risky assets are bought and sold in a usual financial market context in order to obtain the chosen portfolio. Also, we do not impose integer-valued quantities.

3.2.1 Bank should have a positive expected net-worth delta

Expected returns vs interest rates Since investment opportunities' returns are uncertain, investment opportunities must offer a risk premium—although loans to other banks are risky too they are obviously less so .

This implies a first initial condition on the means μ of the vector of increases in relation to the initial prices :

$$\forall l \in [\![1, m]\!], \ \frac{\mu_l}{X_0^l} \geq r$$

Balance sheets coherence Thus it can be interesting for a bank to borrow money from other banks in order to invest. Although it may do so only in such a way that it gains money on average—where $\mathcal{F}_t$ is the information available up to time t :

$$\mathbb{E}[E_t^i | \mathcal{F}_{t-1}] \geq E_{t-1}^i$$

Let us remark first that since $E^i_{t-1} \geq \bar{E}^i$, this implies that a bank that has not defaulted in $t-1$ cannot be expected to default in t.

Applying expectation conditionally on $\mathcal{F}_t$ to (6) we get:

$$\mathbb{E}[E^i_t|\mathcal{F}_{t-1}] = E^i_{t-1} + rL^i_{t-1} - rD^i_{t-1} + Q^i_{t-1}\mathbb{E}[\omega^l_t|\mathcal{F}_{t-1}].$$

Which is equivalent to:

$$\mathbb{E}[E^i_t|\mathcal{F}_{t-1}] - E^i_{t-1} = rL^i_{t-1} - rD^i_{t-1} + Q^i_{t-1}\mu.$$

As a consequence,

$$\mathbb{E}[E^i_t|\mathcal{F}_{t-1}] \geq E^i_{t-1} \Leftrightarrow rL^i_{t-1} - rD^i_{t-1} + Q^i_{t-1}\mu \geq 0.$$

Rearranging the terms, the condition condition is:

$$Q^i_{t-1}\mu \geq r(D^i_{t-1} - L^i_{t-1})$$

Actually this condition may prove too difficult to enforce at each future period. We will thus consider only its initial version:

$$Q^i_0\mu \geq r(D^i_0 - L^i_0). \tag{1}$$

3.2.2 Regulation rules and management conditions

Reserve rule We want to ensure that banks can pay their interest rates the next day. We thus introduce the following regulatory rule imposed by some prudential authority. We take the positive part of the second term since lending more than on borrowed does not yield the right to have negative reserves.

$$R^i_t + r\max(0,\ (L^i_t - D^i_t)) \geq 0 \tag{2}$$

Proposition A bank that has not defaulted in t necessarily has enough liquidity in t to comply with the reserve rule.

To prove this, let us distinguish between two case.

- $\widehat{D}^i_t \leq \widehat{L}^i_t$. In that case, a bank only receives interest rates and thus automatically complies with the reserve rule since its reserves are positive (we do not authorize negative reserves). In other words, since $R^i_t \geq 0$

$$\widehat{L}^i_t - \widehat{D}^i_t \geq 0 \Rightarrow r(\widehat{L}^i_t - \widehat{D}^i_t) \geq 0 \Rightarrow \widehat{R}^i_t + r(\widehat{L}^i_t - \widehat{D}^i_t) \geq 0.$$

- $\widehat{D}^i_t > \widehat{L}^i_t$. The bank has not defaulted in t, thus:

$$\widehat{E}^i_t > \bar{E}^i \Rightarrow \widehat{E}^i_t > 0 \Leftrightarrow \widehat{R}^i_t + \widehat{P}^i_t + \widehat{L}^i_t - \widehat{D}^i_t > 0.$$

We have:

$$\widehat{D}_t^i - \widehat{L}_t^i > \widehat{R}_t^i + \widehat{P}_t^i.$$

Since $r < 1$:

$$\widehat{D}_t^i - \widehat{L}_t^i > r(\widehat{D}_t^i - L_t^i).$$

As a consequence:

$$\widehat{R}_t^i + \widehat{P}_t^i > r(\widehat{D}_t^i - \widehat{L}_t^i).$$

We can thus conclude that a bank that has not defaulted in t always has enough liquidity to be able to reallocate its liquid assets in t so as to comply with the reserve rule. It can do so by selling partially its portfolio in order to increase its reserves.

Thus, this rule enables us to avoid liquidity defaults, and being solvent is a sufficient condition to be able to comply with it. Since we want to account only for solvency defaults, our model is coherent. Indeed, default can be defined as either having not enough cash to honor one's financial obligation (liquidity default) or not having enough equity (solvency default)—or both. We have shown here that since the only illiquid assets are inter-bank loans, if equity is positive in t then by construction liquidity default cannot happen in t.

Portfolio management condition Since the value of the assets in the portfolio will vary, so will the size of the portfolio in relation to the rest of the balance-sheet quantities. As a basic rule of management, we may state that each bank wants to maximize its investment in the portfolio under the constraint that it amounts to a given fraction of the total of its assets $\mathcal{A}_t$ and that it respects the reserve rule. Let us define then by α^i the target investment percentage of bank j which we can interpret as a behavioral parameter. We assume for now that the share of wealth invested in each asset remains constant. As a consequence, we can formulate the problem in term of P_t only :

$$\max_{\substack{P_t^i \leq \alpha^i \mathcal{A}_t^i \\ R_t^i + \max(0,\ r(L_t^i - D_t^i)) \geq 0 \\ P_t^i + R_t^i = \widehat{P}_t^i + \widehat{R}_t^i}} P_t^i$$

3.3 Stage 1 : updates

3.3.1 Reserves

The evolution of reserves is given by:

$$\widehat{R}_t^i = R_{t-1}^i + r\widehat{L}_t^i - r\widehat{D}_t^i \tag{3}$$

3.3.2 Portfolio

By definition :

$$\widehat{P}_t^i = Q_{t-1}^i X_t.$$

Using the dynamics of the risky assets this is equivalent to :

$$\widehat{P}_t^i = Q_{t-1}^i (X_{t-1} + \omega_{t-1}).$$

Supposing that bank i has not defaulted in $t-1$:

$$\widehat{P}_t^i = P_{t-1}^i + Q_{t-1}^i \omega_t. \tag{4}$$

3.3.3 Equity

In math form, the accounting definition of equity is :

$$\widehat{E}_t^i = \widehat{R}_t^i + \widehat{P}_t^i + \widehat{L}_t^i - \widehat{D}_t^i \tag{5}$$

Putting all above dynamic equation together yields:

$$\widehat{E}_t^i = R_{t-1}^i + r\widehat{L}_t^i - r\widehat{D}_t^i + \widehat{L}_t^i - \widehat{D}_t^i + P_{t-1}^i + Q_{t-1}^i \omega_t$$

If no bank has defaulted in $t-1$, we have that $\widehat{L}_t^i = L_{t-1}^i$ and $\widehat{D}_t^i = D_{t-1}^i$, and thus:

$$E_t^i = R_{t-1}^i + P_{t-1}^i + L_{t-1}^i - D_{t-1}^i + r(L_{t-1}^i - D_{t-1}^i) + Q_{t-1}^i \omega_t$$

We can thus deduce the following recursion formula for equity in the case where no bank has defaulted in the previous period:

$$\Leftrightarrow E_t^i = E_{t-1}^i + r(\widehat{L}_{t-1}^i - \widehat{D}_{t-1}^i) + Q_{t-1}^i \omega_t \tag{6}$$

3.4 Stage 3 : balance sheet management

3.4.1 Reserve rule and portoflio rule in practice

Let us distinguish two cases

- $\widehat{R}_t^i < \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i))$ (reserve rule not matched)
- $\widehat{R}_t^i \geq \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i))$ (reserve rule matched)

Let us also define the portfolio valuation objective P_t^j which corresponds to the valuation of the portfolio the bank wish to reach.

Reserve rule matched No need to rebalance to comply with the reserve rule, although if the objective valuation of the portfolio is to be increased, we must keep in mind that the new portfolio objective must also comply with the reserve rule. We distinguish again different cases :

- $\widehat{P}_t^i > \alpha^i \mathcal{A}_t^i$. In that case, a portion $\widehat{P}_t^i - \alpha^i \mathcal{A}_t^i$ of the portfolio must be sold. No other actions are required, thus:

$$P_t^i = \alpha^i \mathcal{A}_t^i.$$

- $\widehat{P}_t^i \le \alpha^i \mathcal{A}_t^i$. In that case the bank wants to increase its portfolio to saturate the constraint if possible given the reserve rule. Thus:

$$P_t^i = \min\left(\alpha^i \mathcal{A}_t^i, \quad \widehat{P}_t^i + \widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i))\right).$$

Reserve rule not matched The bank have to sell a portion of its portfolio to comply with the reserve rule. However, it may sell more if its portfolio is still too large according to the financial choice. Let us distinguish two cases :

- $\widehat{P}_t^i + \widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i)) \le \alpha^i \mathcal{A}_t^i$. In that case, the bank sells only the amount necessary to comply with the reserve rule — since $\widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i)) < 0$ this is indeed selling . As a consequence:

$$P_t^i = \widehat{P}_t^i + \widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i)).$$

- $\widehat{P}_t^i + \widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i)) > \alpha^i \mathcal{A}_t^i$. In that case, the bank sells enough portfolio assets to comply with the financial choice. Which is enough to comply also with the reserve rule since we have: $\widehat{P}_t^i - \alpha^i \mathcal{A}_t^i > -\widehat{R}_t^i + \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i))$. As a consequence:

$$P_t^i = \alpha^i \mathcal{A}_t^i.$$

Synthesis We can actually unify all four cases in the following formula :

$$P_t^i = \min(\widehat{P}_t^i + \widehat{R}_t^i - \max(0,\ r(\widehat{D}_t^i - \widehat{L}_t^i)), \quad \alpha^i \mathcal{A}_t^i). \tag{7}$$

The new amount of reserves is also deduced easily from P_t^i:

$$R_t^i = \widehat{R}_t^i + \widehat{P}_t^i - P_t^i. \tag{8}$$

3.4.2 Find quantities to match a given portfolio valuation objective

Now that P_t^j is optimized, we show here how to adjust the quantities invested in each asset to match this portfolio valuation objective. Given prices X_t and quantities Q_{t-1}^j, we seek to find the vector of quantities Q_t^j for which $Q_t^j X_{t-1} = P_t^j$ while keeping the relative quantities constant. We show how to do this in the appendices A yielding the following result:

$$\forall l, \quad Q_t^{il} = Q_{t-1}^{il}\left(1 + \frac{P_t^i - \widehat{P}_t^i}{\widehat{P}_t^i}\right). \tag{9}$$

Using (7) into (9), we deduce the new quantities:

$$\forall l, \quad Q_t^{il} = Q_{t-1}^{il}\left(1 + \frac{\min(\widehat{P}_t^i + \widehat{R}_t^i - r(\widehat{D}_t^i - \widehat{L}_t^i), \quad \alpha^i \mathcal{A}_t^i) - \widehat{P}_t^i}{\widehat{P}_t^i}\right). \tag{10}$$

4 Taking into account bankruptcy

4.1 Hypothesis and definitions

Set of defaulting banks A time t, if the capital of a non-empty set of banks to drop below a given threshold, those banks declare bankruptcy at time t. Let $\mathcal{D}_t$ be the set of banks that declare bankruptcy at time t. Thus :

$$j \in \mathcal{D}_t \Leftrightarrow \{\widehat{E}_t^j \leq \bar{E}^j\} \cap \{E_{t-1}^j > \bar{E}^j\}$$

We also define the set of banks that have defaulted up to time $t+1$:

$$\mathcal{D}_{0:t} = \bigcup_{s=0}^{t} \mathcal{D}_s$$

Symmetrically, we use the notation $\overline{\mathcal{D}_t}$ the complementary in the set of banks of $\mathcal{D}_t$. We use the same notation for the complementary of $\mathcal{D}_{0:t}$ which we shall then denote by $\overline{\mathcal{D}_{0:t}}$.

Leverage regulatory threshold In order to analyze the effect of a maximum leverage ratio enforced by the regulator, we can decide moreover that any bank which does not satisfy the leverage regulatory threshold is liquidated as a prudential measure. Mathematically let us introduce the leverage regulatory threshold $\lambda^\star$, and at all periods banks must satisfy :

$$\frac{\mathcal{L}_t^i}{E_t^i} \leq \lambda^\star$$

This transforms the definition of the set of defaulting banks :

$$j \in \mathcal{D}_t \Leftrightarrow \left\{\{E_t^j \leq \bar{E}^j\} \cap \left(\frac{\mathcal{L}_t^j}{E_t^j} > \lambda^\star\right)\right\} \bigcap \left\{\{E_{t-1}^j > \bar{E}^j\} \cap \left(\frac{\mathcal{L}_{t-1}^j}{E_{t-1}^j} \leq \lambda^\star\right)\right\}$$

Proceedings from liquidation and claim coefficient Let us firstly introduce two quantities that we will use across this section.

- We define the proceedings from liquidation π_t^j . This is the cash liquidation value of j's balance sheet after it declares default and is liquidated at time t
- We define the claim coefficient of creditor i on bank j by :

$$\Psi_t^{ij} = \frac{\widehat{L}_t^{ij}}{\sum_{s=1}^{n} \widehat{L}_t^{sj}}$$

In this section, we will present two possible procedures to determine π_t^j : internal settlement in section 4.2 and intervention of a third party in section 4.3. Although we firstly present some considerations of the price impact of fire sales.

Impact of fire sale on risky assets' valuation When a portfolio is sold in a fire sale context, an important volume is sold and the selling is done in the urgency. It is as a consequence interesting — realistic — to add a fire sale impact to the valuation of the risky assets sold. There are two dimensions to this impact :

- When a bank is liquidated, it implies that the liquidation value of a portfolio is less than its face value. We model this using the fire sale constant ξ that is introduced in the next section.
- The liquidation of an important volume of a given asset is also bound to have a long term price impact. Such long term impact would be an interesting add-in to our model since for now the price impact is local — affects only the portfolio liquidation of one bank at a time — and memory-less — does not have long term impact on the prices.

4.2 Internal settlement

In the internal settlement case, the loans of a defaulting banks j are redistributed to its creditor proportionally to their claim on j.

1. In $t-1$ at stage 2 :
   - if $\widehat{E}_{t-1}^j \leq \bar{E}^j$, j declares default. Which triggers the following liquidation steps.
   - π_{t-1}^j is computed. Portfolio is sold according to its valuation with a discount coefficient $0 < \xi < 1$ applied due to fire-sale. Reserves are included.

$$\pi_{t-1}^j = \xi \widehat{P}_{t-1}^j + \widehat{R}_{t-1}^j$$

2. In t at stage 1, the default becomes public information which brings about the following modifications :

   - j's loans are added to the loans of the creditors of j proportionally to Ψ^{ij}_{t-1} :

   $$\forall i \notin \mathcal{D}_{0:t-1}, \quad \forall k \notin \mathcal{D}_{0:t-1}, \quad \widehat{L}^{ik}_t = L^{ik}_{t-1} + \Psi^{ij}_{t-1} L^{jk}_{t-1}$$

   - The loans matrix is modified to account for j's default:

   $$\forall i, \quad \widehat{L}^{ij}_t = 0$$
   $$\forall k, \quad \widehat{L}^{jk}_t = 0$$

   The aggregated loans and debts are then computed according to their definition:

   $$\forall i, \quad \widehat{L}^i_t = \sum_{s=1}^{n} \widehat{L}^{is}_t$$
   $$\forall i, \quad \widehat{D}^i_t = \sum_{s=1}^{n} \widehat{L}^{si}_t$$

   - j's balance sheet quantities are set to zero :

   $$(E^j_t, D^j_t, R^j_t, P^j_t, L^j_t, Q^j_t) = (0, 0, 0, 0, 0, 0_{\mathbb{R}^m})$$

   - Proceedings of liquidation are distributed to the creditors of j proportionally to their claim on j. This implies a modified version of the equation (3):

   $$\widehat{R}^i_t = R^i_{t-1} + r(\widehat{L}^i_t - \widehat{D}^i_t) + \Psi^{ij}_{t-1} \pi^j_{t-1}$$

   Let us highlight that since the loans of a defaulting bank are redistributed internally to its non defaulting creditors, the amount of interests paid on loans by each non defaulting bank is not affected by the defaults of other banks. On the other hand, the amount of interests received can decrease since the loans to a defaulting banks are lost.

4.3 Introduction of a third party

Introduction of the liquidator Another option is to introduce a special actor in the system which we call the liquidator. It only intervenes when a bank is liquidated and cannot go bankrupt (it has infinite reserves). Although for reason that will become clear, the liquidator must be integrated to the graph. We shall as a consequence give it a special index: 0.

The balance sheet of the liquidator has a special format :

Assets ($\mathcal{A}_t^0$)	Liabilities ($\mathcal{L}_t^0$)
Reserves ($R_t^0 =$ «∞»)	Equity (E_t^0)
Inter-bank loans (L_t^0)	(Debts ($D_t^0 = 0$))
(Portfolio ($P_t^0 = 0$))	

Liquidation with the liquidator When a bank j goes bankrupt at time $t-1$, the liquidator buys the totality of the bankrupt bank's loans to other banks with a discount $0 < \zeta < 1$. Although, we have to be careful since the bankrupt bank in question may have lent to other defaulting bank. The liquidator does not buy those value-less loans. For the rest the procedure is similar to the previous one :

1. In $t-1$ at stage 2 :
   - if $\widehat{E}_{t-1}^j \leq \bar{E}^j$, j declares default. Which triggers the following liquidation steps.
   - π_{t-1}^j is computed. Portfolio is sold according to its valuation with a discount coefficient $0 < \xi < 1$ applied due to fire-sale. Reserves are included. Finally cash from the loans sold to the liquidator are incorporated

$$\pi_{t-1}^j = \xi \widehat{P}_{t-1}^j + \widehat{R}_{t-1}^j + \zeta \sum_{k \in \overline{\mathcal{D}_{t-1}}} \widehat{L}_{t-1}^{jk}$$

2. In t at stage 1, the default becomes public information which brings about the following modifications :
   - The liquidator's balance sheets is updated to incorporate the loans buy-outs (bank j's debtor now owns money to the liquidator) :

$$\begin{aligned}
\widehat{R}_t^0 &= \widehat{R}_{t-1}^0 - \zeta \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\widehat{L}_t^0 &= L_{t-1}^0 + \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\widehat{E}_t^0 &= E_{t-1}^0 + (1-\zeta) \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\forall k \in \overline{\mathcal{D}_{t-1}}, \quad \widehat{L}_t^{0k} &= L_{t-1}^{0k} + L_{t-1}^{jk}
\end{aligned}$$

   - The loans matrix is modified :

$$\begin{aligned}
\forall i, \quad \widehat{L}_t^{ij} = 0 \\
\forall k, \quad \widehat{L}_t^{jk} = 0
\end{aligned}$$

The aggregated loans and debts are then computed according to their definition:

$$\forall i, \quad \widehat{L}_t^i = \sum_{s=1}^{n} \widehat{L}_t^{is}$$
$$\forall i, \quad \widehat{D}_t^i = \sum_{s=1}^{n} \widehat{L}_t^{si}$$

- j's balance sheet quantities are set to zero :

$$(E_t^j, D_t^j, R_t^j, P_t^j, L_t^j, Q_t^j) = (0, 0, 0, 0, 0, 0_{\mathbb{R}^m})$$

- Proceedings of liquidation are distributed to the creditors of j proportionally to their claim on j. This implies a modified version of the equation (3):

$$\widehat{R}_t^i = R_{t-1}^i + r(\widehat{L}_t^i - \widehat{D}_t^i) + \Psi_{t-1}^{ij} \pi_{t-1}^j$$

5 Synthesis and aggregation of the model

In this section we summarize the fundamental equations of the model.

5.1 Preliminaries

- Definition of risky assets' dynamics:

$$\forall l \in [\![1, m]\!], \quad X_t^l = X_{t-1}^l + \omega_{t-1}^l$$

- No expected losers initial condition

$$\forall i \in [\![0, n]\!], \quad Q_0^i \mu_l \geq r(D_0^i - L_0^i).$$

5.2 Stage 1 of period t

- Update balance sheet of the liquidator

$$\begin{aligned}
\widehat{R}_t^0 &= R_{t-1}^0 - \zeta \sum_{j \in \mathcal{D}_{t-1}} \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\widehat{L}_t^0 &= L_{t-1}^0 + \sum_{j \in \mathcal{D}_{t-1}} \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\widehat{E}_t^0 &= E_{t-1}^0 + (1-\zeta) \sum_{j \in \mathcal{D}_{t-1}} \sum_{k \in \overline{\mathcal{D}_{t-1}}} L_{t-1}^{jk} \\
\forall k \in \overline{\mathcal{D}_{t-1}}, \quad \forall j \in \mathcal{D}_{t-1}, \quad \widehat{L}_t^{0k} &= L_{t-1}^{0k} + L_{t-1}^{jk}.
\end{aligned}$$

- The loans matrix is modified :

$$\forall i \in [\![0,n]\!],\quad \forall j \in \mathcal{D}_{t-1},\quad \forall i,\quad \widehat{L}_t^{ij} = 0$$
$$\forall k \in [\![0,n]\!],\quad \forall j \in \mathcal{D}_{t-1},\quad \forall k,\quad \widehat{L}_t^{jk} = 0.$$

The aggregated loans and debts are then computed according to their definition:

$$\forall i \in [\![0,n]\!],\quad \widehat{L}_t^{i} = \sum_{s=1}^{n} \widehat{L}_t^{is}$$
$$\forall i \in [\![0,n]\!],\quad \widehat{D}_t^{i} = \sum_{s=1}^{n} \widehat{L}_t^{si}.$$

- Zero out the defaulting bank's balance sheet

$$\forall j \in \mathcal{D}_{t-1},\quad (E_t^j, D_t^j, R_t^j, P_t^j, L_t^j, Q_t^j) = (0,0,0,0,0,0_{\mathbb{R}^m}).$$

- Update reserves

$$\forall i \in [\![0,n]\!],\quad \widehat{R}_t^i = R_{t-1}^i + r(\widehat{L}_t^i - \widehat{D}_t^i) + \sum_{j \in \mathcal{D}_{t-1}} \Psi_{t-1}^{ij} \pi_{t-1}^j.$$

- Update portfolios

$$\forall i \in [\![0,n]\!],\quad \widehat{P}_t^i = P_{t-1}^i + Q_{t-1}^i \omega_t.$$

- Update equities

$$\forall i \in [\![0,n]\!],\quad \widehat{E}_t^i = R_{t-1}^i + r(\widehat{L}_t^i - \widehat{D}_t^i) + \sum_{j \in \mathcal{D}_{t-1}} \Psi_{t-1}^{ij} \pi_{t-1}^j + \widehat{L}_t^i + \widehat{P}_t^i - \widehat{D}_t^i.$$

Developing, we can show that there are three possible sources of losses of equity. Let us consider i given:

$$\widehat{E}_t^i = R_{t-1}^i + r(\widehat{L}_t^i - \widehat{D}_t^i) + \sum_{j \in \mathcal{D}_{t-1}} \Psi_{t-1}^{ij} \pi_{t-1}^j + L_{t-1}^i + \widehat{L}_t^i - L_{t-1}^i + \widehat{P}_t^i - \widehat{D}_t^i$$

Using the fact that $\widehat{D}_t^i = D_{t-1}^i$, we can get the following formula:

$$\widehat{E}_t^i = E_{t-1}^i + \underbrace{r(\widehat{L}_t^i - D_{t-1}^i)}_{\downarrow\ net\ loans\ revenues} + \underbrace{\sum_{j \in \mathcal{D}_{t-1}} \Psi_{t-1}^{ij} \pi_{t-1}^j + \widehat{L}_t^i - L_{t-1}^i}_{defaults} + \underbrace{Q_{t-1}^i \omega_t}_{portfolio}.$$

5.3 Stage 2 of period t

- Computation of the proceedings of liquidation

$$\forall j \in \mathcal{D}_{t-1}, \quad \pi_t^j = \xi \widehat{P}_t^j + \widehat{R}_t^j + \zeta \sum_{k \in \overline{\mathcal{D}_{t-1}}} \widehat{L}_t^{jk}.$$

- Compute the claim coefficients

$$\forall i \in [\![0, n]\!], \quad \forall j \in \mathcal{D}_{t-1}, \quad \Psi_t^{ij} = \frac{\widehat{L}_t^{ij}}{\sum_{s=1}^{n} \widehat{L}_t^{sj}}.$$

5.4 Stage 3 of period t

- Portfolio management : set the definitive portfolio valuation for $t+1$

$$\forall i \in \overline{\mathcal{D}_{t-1}}, \quad P_t^i = \min(\widehat{P}_t^i + \widehat{R}_t^i - r(\widehat{D}_t^i - \widehat{L}_t^i), \quad \alpha^i \mathcal{A}_t^i)$$

- Update the quantities consequently

$$\forall i \in \overline{\mathcal{D}_{t-1}}, \ \forall l \in [\![0, m]\!], \ Q_t^{il} = Q_{t-1}^{il} \left(1 + \frac{\min(\widehat{P}_t^i + \widehat{R}_t^i - r(\widehat{D}_t^i - \widehat{L}_t^i), \quad \alpha^i \mathcal{A}_t^i) - \widehat{P}_t^i}{\widehat{P}_t^i} \right)$$

- Set the definitive reserves for $t+1$ accordingly

$$\forall i \in \overline{\mathcal{D}_{t-1}}, \quad R_t^i = \widehat{R}_t^i + \widehat{P}_t^i - P_t^i$$

Appendices

A Find quantities to match a given portfolio valuation

We show here how to adjust the quantities invested in each asset to match a portfolio valuation objective. This will be useful in the other rebalancing stages.

Given a portfolio value objective P_t^i, a portfolio current valuation $\widehat{P}_t^i$, prices X_{t-1} and quantities Q_{t-1}^i, we seek to find the vector of quantities Q_t^i for which $Q_t^i X_{t-1} = P_t^i$ while keeping the relative quantities constant i.e :

$$\forall l \in [\![1, m]\!], \quad \frac{Q_t^{il}}{\sum_{c=1}^{m} Q_t^{ic}} = \frac{Q_{t-1}^{il}}{\sum_{c=1}^{m} Q_{t-1}^{ic}}$$

Let us define :

$$Q_{t-1}^{\bar{i}} = \sum_{c=1}^{m} Q_{t-1}^{ic}$$

$$\delta^{il} = \frac{Q^{il}_{t-1}}{Q^{\bar{i}}_{t-1}}$$

It is easy to verify that given the constraints, we only have one degree of freedom to modify the quantities and thus finding Q^i_t boils down to finding η^i such that :

$$\sum_{l=1}^{m} (Q^{il}_{t-1} + \delta^{il}\eta^i) X^l_t = P^i_t$$

The resulting solution quantities being :

$$\forall l, \quad Q^{il}_t = (Q^{il}_{t-1} + \delta^{il}\eta^i)$$

Developing and solving in η^i yields :

$$\eta^i = Q^{\bar{i}}_{t-1} \frac{P^i_t - \widehat{P}^i_t}{\widehat{P}^i_t}$$

Thus :

$$\forall l, \quad Q^{il}_t = Q^{il}_{t-1} \left(1 + \frac{P^i_t - \widehat{P}^i_t}{\widehat{P}^i_t} \right)$$

B Initialization given a loans structure

We describe in this appendix how we go about initializing the balance sheets quantities once a weighted and directed graph is given. Obviously this graph entirely characterizes the matrix of loans L, and as a consequence the variables L^i_0 and D^i_0 for all the banks. This gives us two degrees of freedom :

- The choice of equities which implicitly determines the amount of liquid assets $(P^i_0 + R^i_0)$
- The choice of the division of liquid assets between portfolio and reserves.

B.1 Constraints

Although we need to initialize such that the following constraints are satisfied:

- The condition (1) :
$$Q^i_0 \mu \geq r(D^i_0 - L^i_0).$$
- The reserve rule (2):
$$R^i_0 \geq \max(0,\ r(D^i_0 - L^i_0)).$$

- A liquid asset postivity rule : Equity must be chosen such that the liquid assets $(P_0^i + R_0^i)$ are positive, which is equivalent to :

$$E_0^i \geq L_0^i - D_0^i$$

- A leverage objective :

$$\frac{\mathcal{L}_0^i}{E_0^i} \leq \beta^i \lambda^\star.$$

Where $\lambda^\star$ is a regulatory leverage threshold and β is a behavior parameter for the banks. Since $\mathcal{L}_0^i = E_0^i + D_0^i$, the leverage objective can be rewritten as :

$$1 + \frac{D_0^i}{E_0^i} \leq \beta^i \lambda^\star.$$

Since $\frac{D_0^i}{E_0^i} \geq 0$, we must have :

$$\beta^i \lambda^\star \geq 1 \Leftrightarrow \beta^i \in [\frac{1}{\lambda^\star}, 1].$$

This interval being valid since $\lambda^\star \geq 1$.

The leverage condition can be reformulated as :

$$E_0^i \geq \frac{D_0^i}{\lambda^\star \beta^i - 1}.$$

Let us define the leverage lower bound on equity by :

$$E_0^{i\star} = \frac{D_0^i}{\lambda^\star \beta^i - 1}.$$

B.1.1 Rewriting of the first constraint in terms of portfolio

Let us first focus on the first condition since it needs to be transformed to be expressed as a condition on P_0^i. Firstly, as stated earlier, the relative quantities invested in each assets are given for each bank.

Let us denote by $q^i \in \mathbb{R}^m$ the vector of the relative fractions invested in the risky assets for bank i. As a consequence, we have :

$$Q_0^i = p^i q^i$$

Let us also introduce the portfolio size variable $p^i \in \mathbb{R}^+$. Using this variable, we can characterize P_0^i using the following equality :

$$P_0^i = p^i q^{iT} X_0.$$

To finish with, we normalize the initial values of all assets, meaning that

$$X_0 = x_0 \mathbf{1}_{\mathbb{R}^m}.$$

.

As a consequence,

$$P_0^i = p^i q^{iT} x_0 \mathbf{1}_{\mathbb{R}^m} = x_0 p^i$$

Now, we introduce the variable :

$$\tilde{\mu}^i = q^{iT} \mu.$$

We have :

$$p^i \tilde{\mu}^i = Q_0^i \mu.$$

And thus :

$$P_0^i \tilde{\mu}^i = x_0 Q_0^i \mu.$$

Which finally implies :

$$P_0^i \frac{\tilde{\mu}^i}{x_0} = Q_0^i \mu.$$

We can as a consequence rewrite the condition (1) in terms of portfolio as :

$$P_0^i \frac{\tilde{\mu}^i}{x_0} \geq r(D_0^i - L_0^i).$$

B.2 Choosing equities

We now want to choose equities such large enough such that the constraints can be satisfied.

Conditions (1) and (2) can be written respectively as :

$$P_0^i \geq \frac{x_0}{\tilde{\mu}^i} r(D_0^i - L_0^i)$$

$$R_0^i \geq r(D_0^i - L_0^i).$$

Summing the two, we get :

$$P_0^i + R_0^i \geq r(D_0^i - L_0^i)(\frac{x_0}{\tilde{\mu}^i} + 1).$$

Adding L_0^i and subtracting D_0^i on both sides we get :

$$P_0^i + R_0^i + L_0^i - D_0^i \geq r(D_0^i - L_0^i)(\frac{x_0}{\tilde{\mu}^i} + 1) + L_0^i - D_0^i.$$

Which is equivalent to :

$$E_0^i \geq (D_0^i - L_0^i)(r\frac{x_0}{\tilde{\mu}^i} + r - 1).$$

Let us define then the quantity :

$$\tilde{E}_0^i = (D_0^i - L_0^i)(r\frac{x_0}{\tilde{\mu}^i} + r - 1).$$

We must then choose the initial equity such that it implies enough liquid asset via the above condition and such that it also respects the leverage objective. To finish with, the implied sum of liquid assets must be positive. This can be stated synthetically using the following inequality :

$$E_0^i \geq \max(\tilde{E}_0^i, E_0^{i\star}, L_0^i - D_0^i)$$

B.3 Defining portfolio and reserves

Once the equity has been chosen, the sum $P_0^i + R_0^i$ is implicitly also chosen since $P_0^i + R_0^i = E_0^i - L_0^i + D_0^i$

We can then choose P_0^i and R_0^i solving the following optimization problem :

$$\max_{\substack{P_0^i \leq \alpha^i \mathcal{A}_t^i \\ R_0^i \geq r(D_0^i - L_0^i) \\ P_0^i + R_0^i = E_0^i - L_0^i + D_0^i \\ P_0^i \geq \frac{x_0}{\tilde{\mu}^i} r(D_0^i - L_0^i)}} \quad P_0^i$$

In order to avoid non feasibility, we must ensure when choosing α_i that :

$$\alpha_i \mathcal{A}_0^i \geq \frac{x_0}{\tilde{\mu}^i} r(D_0^i - L_0^i).$$

Which is equivalent to :

$$\alpha_i \geq \frac{x_0 r(D_0^i - L_0^i)}{\mathcal{A}_0^i \tilde{\mu}^i}.$$

If α_i is chosen this way, we can apply the same resolution as in the financial choice problem. We have chosen the equity such that it is large enough to satisfy both conditions ((1) and (2))and we maximize the value of the portfolio thus the choice of α_i described above alone ensures that the above problem and the financial choice problem in $t = 0$ are equivalent :

$$\max_{\substack{P_0^i \leq \alpha^i \mathcal{A}_t^i \\ R_0^i \geq r(D_0^i - L_0^i) \\ P_0^i + R_0^i = E_0^i - L_0^i + D_0^i}} \quad P_0^i$$

Only the equality constraint is different. Taking this into account yields the solution :

$$P_0^i = \min(E_0^i - L_0^i + D_0^i - r(D_0^i - L_0^i), \quad \alpha^i \mathcal{A}_0^i).$$

Factorizing by $(D_0^i - L_0^i)$:

$$P_0^i = \min(E_0^i + (1-r)(D_0^i - L_0^i), \quad \alpha^i \mathcal{A}_0^i).$$

We deduce the reserves directly from there :

$$R_0^i = E_0^i - L_0^i + D_0^i - P_0^i$$

Since :

$$p^i = \frac{P_0^i}{x_0},$$

and :

$$Q_0^i = p^i q^i,$$

We can easily deduce the initial quantities :

$$Q_0^i = \frac{P_0^i}{x_0} q^i.$$

C Indicateurs

C.1 Méthodologie

Voir sur quelques exemples

C.2 Banques

- Nombre de défaut : soit la version courbe (CDF des défauts)ou alors version ponctuelle au temps t combien de banques ont fait défaut ?
- Somme des pertes en capital dûes uniquement aux banqueroutes. Deux canaux : pertes sur les prêts morts, pertes sur la différence de vente du portefeuille dûe aux fire sales.

C.3 Réseau

- Nombre d'arrêtes totale
- Evolution de la structure même (proxy : l'évolution du nombre moyen de contreparties) : comment évolue le degré moyen ? A mettre en relation avec l'indicateur précédent. Regarder aussi les degrés max et les degrés min ainsi que la variance (hétérogénéité des degrés au sein du réseau). Version courbe : distribution du degré.

- Version plus avancée : y a-t-il des cliques qui apparaissent ? Si on part d'un réseau complètement connecté, il converge vers quoi comme réseau ? Faire de la détéction de cliques. Y a-t-il des composantes clusters qui apparaissent (spectral clustering). En partant d'un réseau donné, en moyenne va-t-il se scinder en 3, 4... composantes peu reliées entre elles ou non ?

D Simulations

Au regard du nombre de degré de liberté et des temps de calcul, il faut cadrer nos simulations.

- Pour le côté Monte Carlo sur les trajectoires de prix (le plus couteux), on peut limiter l'aléa en fixant une fois pour toutes $m = 2$. Cela fait que l'on peut espérer une "convergence" plus rapide que si l'on avait plus de sources d'aléas.
- Pour l'effet de la diversification, se limiter à deux cas : totale diversification avec $(0.5, 0.5)$ de quantités relatives pour tout le monde, et le cas concentration maximale avec $(1, 0)$ ou $(0, 1)$ equirépartis aléatoirement sur les banques.
- Pour les valeurs du leverage, un petit nombre de valeurs significatives, $(3, 5, 10)$ ou $(3, 5, 7, 10)$.
- Pour les autres hyperparamètres (hors paramètres de graphes dont on veut étudier l'effet), il faut les fixer, pas vraiment d'autres choix.

E Notes

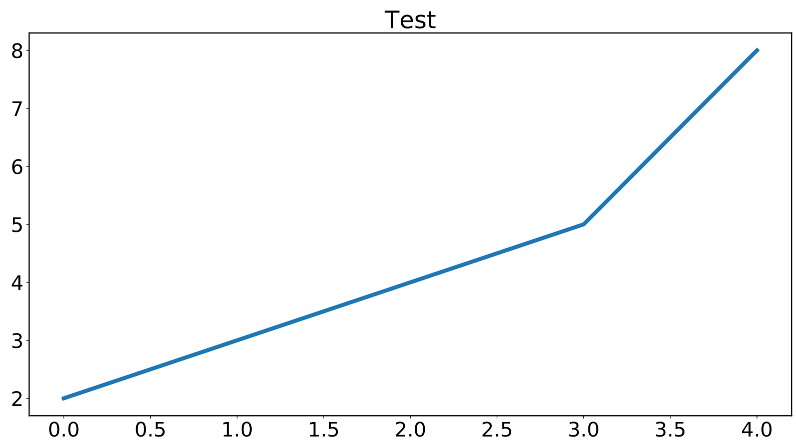
Choisir un vocabulaire spécifique pour les deux sources d'aléas : scenarios/trajectoire de prix (sampled price trajectories) et configuration initiale (initial conditions). "Full sample" pour les deux à la fois, ou "sample pair"

le graphe des averages degrees :

- Y a t-il une sorte de limite pour le leverage = 10 ? Faire sur des périodes plus longues si on atteint une limite. Dépend elle de la connectivité initiale ? Comment depend elle du leverage ? Cette limite est-elle 0 ?

Sur le graphe des cumulatives defaults :

- Les croisements sont -ils des artefacts de l'aléatoire ? Lambda star : quantité max de risque autorisée.
- On peut faire des variantes sur le beta : tout le monde est à lambda star, ou tout le monde est réparti uniformément entre 1 et lambda star ?



- Pour chacune des courbes, compter deux paniers de défauts : $+1$ parce que la banque se sont cassé la gueule, $+1$ dans l'autre pour les défauts liés au leverage. La différence vient-elle du fait que le régulateur enlève plus de monde ou parce que c'est structurellement plus de cassage de gueule.
- A paramètre ER (graphe) donné, comment évolue les défauts en fonctions de lambda star ?

Sur le calcul de la perte :

- Les pertes sur les fire sale, voire à ne pas tout compter en fonction de ce qui est regagné via la liquidation.
- Mettre en fraction de la valeur initiale du réseau
- Interprétation comme perte pour le reste du monde (sur les dépots)

Sur les probas

- On peut se fixer un seuil de pourcentage du réseau mort correspondant à un évènement systémique et dire à telle période, tel réseau dépasse la proba à 0.5 (seuil arbitraire à déterminer) de faire une crise systémique.
- Voir sensibilité au paramètre de départ

Idée : fixer un horizon temporelle et faire des graphes en 3d en fonction de lambda, le p du graphe, et l'indicateur en diminuant le nombre d'échantillonage.

Enregistrer juste ce qui est utile pour pouvoir aller plus vite.