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Simulating fire-sales in a banking and shadow banking system

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Abstract

We develop an agent based model of traditional banks and asset managers. Our aim is to investigate the channels of contagion of shocks to asset prices within and between the two financial sectors, including the effects of fire sales and their impact on financial institutions' balance sheets. We take a structural approach to the price formation mechanism as in Bluhm, Faia and Kranen (2014) and introduce a clearing mechanism with an endogenous formation of asset prices. Both types of institutions hold liquid and illiquid assets and are funded via equity and deposits. Traditional banks are interconnected in the money market via mutual interbank claims, where the rate of return is endogenously determined through a tâtonnement process. We show how in such a set-up an initial exogenous liquidity shock may lead to a fire-sale spiral. Banks, which are subject to capital and liquidity requirements, may be forced to sell an illiquid security, which impacts its, endogenously determined, market price. As the price of the security decreases, both agents update their equity and adjust their balance sheets by making decisions on whether to sell or buy the security. This endogenous process may trigger a cascade of sales leading to a fire-sale. We find that, first, mixed portfolios banks act as plague-spreader in a context of financial distress. Second, higher bank capital requirements may aggravate contagion since they may incentivise banks to hold similar assets, and choose mixed portfolios business model which is also characterized by lower levels of voluntary capital buffer. Third, asset managers absorb small liquidity shocks but they exacerbate contagion when liquid buffers are fully utilised.

Keywords: Fire sales; contagion, systemic risk, asset managers, agent based model.

JEL-Classification: C63, D85, G21, G23

Non-technical summary

Shadow banks have been gaining prominence in recent years as an alternative intermediation vehicle in the financial system. They do not replace traditional banking but coexist as an important and growing market, providing financing to the economy and shaping the liquidity conditions in the financial markets. As the share of shadow banks assets in the total assets of the financial sector increases, concerns about financial stability implications mount. At the same time, banking and shadow banking sectors are increasingly intertwined. Is the traditional banking system more susceptible to idiosyncratic shocks stemming from other banks or from shadow banks? What are channels of transmission of shocks between the two sectors?

To shed light on these issues, we develop an agent based model of profit maximising traditional banks and asset managers, the first funded via equity and deposits, the latter via participations. Both types of institutions hold liquid and illiquid assets, and the risk free rate of return in the interbank lending market and the price of investment security are endogenously determined. Traditional banks are constrained by capital and liquidity requirements. In addition, both banks and asset managers hold discretionary liquidity buffers on top of the regulatory ones. All institutions are indirectly connected through holdings of similar securities, while traditional banks are also interlinked via interbank lending. These two channels determine the dynamics of contagion. In such a set-up we show how an idiosyncratic liquidity shock propagates through the system affecting both interbank market and, if sizable enough, can trigger a fire-sale of the non-liquid security.

When the market for the security opens, banks and asset managers can buy or sell their assets. The interplay of endogenous supply and demand determines the price of the security. Its market price is then used to mark-to-market asset values on banks' and asset managers' balance sheets. This can trigger further rounds of portfolio adjustments both in the interbank lending market and in the security market, as banks need to adjust their balance sheets to meet the regulatory requirements as asset managers as they face redemptions due to drops in the security price. Finally, banks default when, even after fire-selling the assets, they are not able to meet either their interbank obligations or the regulatory requirements. The results in the paper suggest that banks with mixed portfolios, i.e. investing in both bank lending and security, act as a plague spreader. When the initial plague-spreader bank has interbank claims on its balance sheet, it will start a chain of withdrawals which can lead to a fire-sale. Instead, if either the shock is absorbed by the system or if it happens that banks involved in the recalls of interbank lending do not hold the security on their balance sheets, a fire-sale can be mitigated and the incidental contagion will involve only a limited group of banks –precisely those connected through interbank lending.

We also find that asset managers could act as shock absorbers but only for a relatively small shocks and when they have excess liquidity. Small liquidity shocks originating in the asset manager sector are absorbed because these institutions do not need to readjust their balance sheets to meet the regulatory requirements and hence are flexible in using their excess liquidity buffers to cushion the shocks.

Finally, an increase of minimum capital requirement might exacerbate the contagion effect by stimulating an excess supply of (relatively safer) interbank money lending, that consequently depresses the risk free return rate and makes the security market relatively more profitable. As a result, more banks will opt for a mixed portfolio investment strategy, making business models more homogeneous and thus increasing the probability of contagion in the sector. This dynamics goes hand in hand with the presence of a more rigid banking sector that is less able to absorb the initial shocks by providing demand for the risky asset to ease the fire-sale.

1 Motivations

Shadow banks or "Banking Beyond Banks" (Constâncio, 2014) have been gaining prominence in recent years as an alternative source of intermediation in the financial system. They do not replace the traditional banking but coexist as an important and growing market, providing credit to the economy and shaping the liquidity conditions in the financial markets.

The emergence of shadow banks is a result of large liquidity pools that investors have sought to place in safe assets other than in banks' insured deposits. This has raised relevant questions on potential imbalances building up in the financial system related to the nature and the dynamics of shadow banks and their interactions with the traditional banks. As the share of shadow banks assets in the total assets of the financial sector increases, concerns about financial stability implications mount. Ari et al. (2016) using a general equilibrium set-up with shadow bank endogenous entry find that the sector has a natural tendency to grow until it ferments systemic risk. Is the traditional banking system more susceptible to shocks either stemming from banks or from shadow banks? What are channels of transmission of shocks between regulated and unregulated sectors?

Regulators have already been trying to address some of these risks, e.g. by implementing risk-sensitive capital requirements for banks' investments in the equity of funds or the supervisory framework for measuring and controlling banks' large exposures or by proposing haircuts on non-centrally cleared securities financing transactions or by defining potential limits to the collateral reuse. However, research supporting decisions on relevant and reliable regulatory tools and on their actual implementation is yet to advance.

In addition, since the data on shadow bank activities are still scarce, some simulation-based models, in particular agent-based ones, operating with some stylised assumptions can be a valuable approach to get insight into the mechanisms of the interplay between banks and shadow banks and on potential sources of contagion. We follow this avenue in our paper and develop an analytical framework with an endogenous price formation to study contagion risk involving traditional banks and asset managers, including the emergence of fire sales. We then study the effectiveness of bank capital and liquidity requirements in containing these risks.

In our framework both types of agents, traditional banks and asset managers, are profit maximizing. Both types of institutions hold liquid and illiquid assets and are funded via equity and deposits or participations. Traditional banks are constrained by capital and liquidity requirements. In addition, both agents have a discretionary liquidity buffer on top of the regulatory one.

We solve the model by determining the equilibrium in the interbank lending market and in the security market. Then we run simulations whereby an idiosyncratic liquidity shock hits individual banks or assets mangers and observe how the shocks propagate through the system. A bank with a liquidity shortfall can initiate a chain of bank lending callbacks, and—when this is not enough—can starts selling the non-liquid security.

When the market for the security opens, other banks and shadow banks can buy the sell the asset. In our framework the price of the security is endogenously determined as an outcome of the interplay between supply and demand. Once the market price of the security changes, asset holdings in the portfolios of agents are marked-to-market. This can trigger further adjustments both in the interbank lending market and in the security market due to the balance sheet adjustments. Banks re-optimise their balance sheets in order to meet regulatory requirements, while asset managers satisfy redemptions. The redemptions, in turn, emerge as the security price drops below a certain threshold. Finally, banks default when, even after fire-selling the assets, they are not able to meet either their obligations or the imposed requirements.

The paper is organized as follows: in Section 2 we review the relevant literature. In Section 3 we explain the underlying theoretical model, the behaviour of banks and asset managers, the equilibrium in the interbank lending market, the creation of the network of banks, the simulation of shocks, their propagation and the full dynamics of the system. In Section 4 we present the results of the simulations and in Section 5 we conclude.

2 Relevant Literature

In the last decade numerous studies tried to tackle the issue of systemic risk in an interbank network. According to this literature strand the intensity of contagion depends, among other things, on the network structure determined by direct and indirect connections of the financial institutions composing the system.

A highly interconnected network where most banks are linked to many other banks has two features: it can be a source of risk sharing and diversification since the shocks can be spread broadly across many institutions (see, e.g., Allen and Gale (2000); Freixas et al. (2000)), but it can also be a source of contagion due to the too many linkages to other institutions, that carries along higher possibility of being indirectly hit by shocks (Battiston et al., 2012).

A similar idea is well developed by Gai and Kapadia (2010), who suggest a *robust-yet-fragile* tendency of financial networks: even if in the first place the probability of contagion may be very low thanks to numerous but narrow connection channels, the second-round effects can be widespread precisely for the same reason.[1]

The pioneering paper of Cifuentes et al. (2005) looks into the necessity of liquidity and capital buffers to dampen the systemic effects. The authors build a theoretical framework of interconnected financial institutions subject to solvency constraints and the requirement of marking-to-market their assets, and explores the interaction of two possible channels of contagion: a direct effect, that goes through the direct balance-sheet exposure among banks, and an indirect one, that operates via changes in the asset prices and consequent fire-sale spillovers.

The term *fire-sale* was first used to refer to the custom of selling at discounted prices the goods damaged by fire or smoke; by analogy it is now commonly used to indicate the (forced) sale of an asset at an altered, i.e. lower, price. The sale, usually forced by the need of liquidity to pay creditors, takes place at a price lower than the current market price because: since the highest bidders on the demand side might be involved in similar dynamics or have no available liquidity to buy the asset, sellers have to turn to bidders with lower valuations of the asset. As banks are marking to market, the temporary loss in value of the asset induces balance sheets adjustment to the neighbouring institutions holding the same asset, and might consequently cause additional sales and, ultimately, downward spirals that spreads financial distress across institutions. A relatively new stream of literature has tried to explain and reproduce the fire-sale dynamics as cascade effects (Greenwood et al., 2015; Shleifer and Vishny, 2011), with complex financial networks (Caballero and Simsek, 2013), or by quantify the vulnerability of the system to fire-sale spillovers (Duarte and Eisenbach, 2014).

Building on Cifuentes et al. (2005) structural model of interconnected bank balance sheets and endogenous asset markets, Cecchetti et al. (2013) develop a theoretical framework with fire-sales to analyse the resilience of different banking networks to systemic shocks, Bluhm and Krahnen (2011) and Bluhm and Krahnen (2014) consider the emergence of systemic risk and the relations between capital buffers and systemic risk charges (i.e. taxes levied on banks related to their contribution to systemic risk) and study the consistency of two macroprudential policies: capital requirements and systemic risk charge; Bluhm et al. (2014) adds to a very similar environment the presence of a central bank that injects or withdraws liquidity on the interbank lending market in order to reach the targeted interest rate, and conclude that the supply of liquidity from the central bank generally increases systemic risk.

A recent work by Cont and Schaanning (2015) simulates fire-sales affecting institutions through price-mediated contagion: an initial loss in value of illiquid assets forces banks to fire-sale, affecting also liquid assets due to portfolio adjustment in order to adapt leverage ratios. They identify amplification effects due to both leverage constraints and also due to overlapping portfolios across institutions, and underline the non-linearity in response caused by the threshold reaction in deleveraging. In a somehow similar fashion but with different approaches, Chen et al. (2014), Caccioli et al. (2015), Bookstaber and Paddrik (2014), Caccioli et al. (2014) explore the combined effects of two channels of shock propagation among the agents involved in the (interconnected) financial system: a direct channel represented by the counterparty failure risk and an indirect one, working through overlapping portfolios.

Halaj and Kok (2013) simulate a randomly generated distribution of possible network of mutually exposed banks, among which one is hit by a shock that propagates via default on all its interbank payments, banks are allowed to adjust their balance sheets and can liquidate their securities portfolio to meet capital requirements, thus triggering a fire-sale. They analyse the contagion dynamics and confirm that it is strongly non-linear and heterogenous across network configurations.

Another strand of literature deals with shadow banks and its interactions with banks and the optimal policy in such a dual system.

A shadow bank is a financial intermediary (e.g. asset mangers, hedge funds, money market mutual funds, pension funds) that actively participates to the global financial system, although, as they do not accept traditional bank deposits, they do not fall into the Basel III perimeter, thus they are not subject to the regulations applied to conventional banks. On the other hand, shadow banks cannot access public sources of liquidity (the lender of last resort) or public sources of insurance (deposit insurance) and, as such, in times of crisis, can act as vehicles of shocks propagation. Some papers suggest that the creation of shadow banks was a consequence of the the imposition of liquidity and capital requirements on traditional banks that led to the creation of these alternative financial entities, whereby traditional banks shifted the risks they no longer were allowed to bear outside of the regulatory parameter (Gorton and Metrick, 2010; Ordonez, 2013). Other papers consider shadow banks as an alternative banking strategy which involves greater risk-taking at the expense of being exposed to “fundamental runs” on the funding side (Ari et al., 2016).

The presence of shadow banks in the financial markets seemed to be one of the biggest issues that undermined the effectiveness of these regulatory measures(Pozsar et al., 2010). Therefore, since the shadow banking system has rapidly grown after the year 2000, many studies tried to include shadow banks into the analysis of the wider financial panorama, to explore the interactions between the two systems, inspect the systemic risk implications (Maeno et al., 2014; Luttrell et al., 2012) and look for potential regulation solutions(Schwarcz, 2012). Plantin (2014) studies the

[1]For a full survey about interbank network literature we refer to Huser (2015).

optimal prudential policies of banks in presence of a shadow banking sector. To a model with perfect enforcement of optimal bank regulation he adds shadow banks that can bypass the imposed constraints. A trade-off between two regulatory responses is discussed: a tighter capital requirement might bring stability in the banking sector, yet triggering an increase in the shadow banking activity; while a looser one leaves more ground to risk in the official banking sector but also takes shadow banks' activity back in the regulatory perimeter. In a framework of banks with low and high reputation that self-select into traditional or shadow banking activity respectively, a novel regulation that mixes traditional capital requirement and cross-subsidization is proposed by Ordonez (2013), with the intention of avoiding too stringent government regulations that would push shadow banks' activity even further. Ari et al. (2016) analyse policy interventions aimed at alleviating the fire-sales. While asset purchases fuel further expansion of the shadow banking sector, financial stability is achieved with a Pigouvian tax on shadow bank profits.

Illustrations of economic rationale, potential risks and proposals for financial stability policies are given by Adrian (2014) in three specific cases of shadow bank activities, namely the agency mortgage real estate investment trusts, leveraged lending, captive reinsurance affiliates. The author underlines the difficulty of finding a regulation that can apply to all categories of the sector.

Agent Based Modelling is used by Bookstaber and Paddrik (2014) to analyse the dynamic interactions of a network of financial agents who borrow, lend and invest, and trace the path of a variety of shocks deriving from the agents in the system. They simulate fire-sales and follow the propagation of the initial shock among the actors, given that they have different constraints and behavioural assumptions. Consistently with our findings, the model shows that the extent of losses in the system relies more in the reactions to the initial shock rather than in the shock itself.

3 The Model

3.1 Maximization Problem

The model is composed by a total of $(N_B + N_{SB})$ financial institutions that belong either to the set of banks ($\mathcal{B}$) or to the set of Asset Managers ($\mathcal{SB}$), indexed respectively with $i \in \mathcal{B}$ where $\mathcal{B} = \{1, 2, \ldots, N_B\}$, and $m \in \mathcal{AM}$, where $\mathcal{AM} = \{1, 2, \ldots, N_{AM}\}$. The two kinds of institutions are differentiated in two main respects: the investment possibilities and the regulatory constraints they need to respect when choosing their optimal balance sheet structure.

Banks and asset managers are initially endowed with an exogenously given amount of Deposits (D) and Equity (E) for the first, and Participations (P) for the second that they can keep liquid as Cash (C) or invest in a non liquid security (S); moreover traditional banks invest half of their assets in Loans which are a long term "sticky" investment, not easily disposable in the short term. Moreover, bank can access the interbank lending market (IBLM) where they can lend to (bank lending: BL) or borrow from other banks (bank borrowing: BB).

Bank i Balance Sheet

Assets	Liabilities
Cash (C^i) Bank Lending (BL^i) Non-Liquid Assets (S^i) Loans (L^i)	Deposits (D^i) Bank Borrowing (BB^i) Equity (E^i)

Asset manager m Balance Sheet

Assets	Liabilities
Cash (C^m) Non-Liquid Assets (S^m)	Participations (P^m)

Banks and initially endowed with an exogenously given amount of deposits and equity. Asset managers are funded with investors' participations.[2]

3.1.1 Bank optimisation problem

The profit function of a generic Bank i is simply defined as the difference between the revenues from investments and the cost of funding: $\Pi^i = \pi^{assets^i} - cost^{liabilities^i}$. Assuming that the bank can deposits and equity are given,

2

D^i Deposits follow a $N(500000, 100000)$;

E^i Equity follow a $N(65000, 10000)$

P^m Participations follow a $N(500000, 100000)$.

and loans are sticky, the short-term profits of bank i are given by

$$\pi^i = \pi^{investing^i} + \pi^{bank\_lending^i} - cost^{bank\_borrowing^i}$$

, with

$$\begin{aligned} \pi^{investing^i} &= \frac{r_i^s}{p^{mkt}} \cdot S^i \\ cost^{borrowing^i} &= (r^{rf} + r^{PD_i}) \cdot BB^i \\ \mathbb{E}(\pi^{lending^i}) &= (1 - PD^j) \cdot BL^{ij} \cdot (r^{rf} + r^{PD_j}) + PD^j \cdot (BL^{ij} - \xi BL^{ij}) \cdot (r^{rf} + r^{PD_j}) \end{aligned}$$

where

p^{mkt} is the current market price of the security at which banks and asset managers buy and sell; the market price changes in time and a key element for the model is the fact that the non liquid asset is marked to market, so when its market value decreases, banks need to update the book value and register losses on capital accordingly; this particular characteristic allows for triggering of fire-sales spirals;

S^i $= nla^i \cdot p^{mkt}$, is the book value of the nla^i units of the security that bank i holds in its portfolio, at the current market price p^m;

$\frac{r_i^s}{p^{mkt}}$ is the return on the non liquid asset. r_i^s follows a $U(0, 0.15)$; heterogeneity of returns on security reflects the fact that banks are different in the profitability of their investments opportunities due to their past financial activity. This heterogeneity implies that distinct banks will find it more or less profitable to invest in the interbank rather than in asset market;

PD^i is the *Probability of Default* of bank i, it is common knowledge and it follows a $\beta(1, 20)$ probability.

r^{rf} is the risk-free interest rate on the interbank lending, determined through a tatônnement process that takes place in the interbank lending market;

r^{PD_i} is a premium linked to the probability of default of the borrowing bank;

ξ is the *Loss Given Default* in percentage terms, it is common to all banks, constant through time, exogenously given. Set to 0.4, it determines the amount of assets that is lost when a counterparty defaults;

Moreover, since creditors charge a fair risk premium, i.e. their expected profits from bank-lending are the same as what they would earn without risk, $\mathbb{E}(\pi^{BL^{ij}}) = BL^{ij} \cdot r^{rf}$, we derive[3]

$$\mathbb{E}(\pi^i) = r^{rf} \cdot BL^i + \frac{r_i^s}{p^{mkt}} \cdot S^i - r^{rf} \frac{1}{1 - \xi PD^i} \cdot BB^i \tag{1}$$

A traditional bank faces the traditional budget constraint that imposes assets equalizing liabilities

$$C^i + BL^i + S^i + L^i = D^i + BB^i + E^i \tag{2}$$

and a structural budget constraint that sees half of the bank's liabilities to be invested in sticky loans

$$L^i = \frac{D^i + BB^i + E^i}{2} \tag{3}$$

Regulatory Constraints Consistently with Basel III regulatory framework[4], banks are constrained in their investment activities by a liquidity requirement – that expects banks to keep a minimum amount of liquid assets (e.g. cash) to face potential liquidity shocks and requests – and a capital regulatory ratio that requires that Tier 1 and Tier 2 capital must be at least $\gamma_{min}\%$ of the risk weighted assets at all times. Banks periodically check if their portfolios comply with the regulatory requirements and proceed with the necessary adjustments.

[3]For a full derivation of the equation please refer to Appendix A

[4]`http://www.bis.org/publ/bcbs238.pdf`

Capital Requirement - [CpR] Given the structure of our model, we define the equity ratio γ of bank i as

$$\begin{aligned}\text{Equity Ratio}_i = \\ \gamma_i &= \frac{\text{Total Capital}}{\text{Risk Weighted Asset}} \\ &= \frac{C^i + S^i + BL^i + L^i - D^i - BB^i}{\chi_S \cdot S^i + \chi_{BL} \cdot BL^i + \chi_L \cdot L^i}\end{aligned} \tag{4}$$

where χ_S, χ_{BL} and χ_L are the risk weights for security, interbank deposits and loans, respectively set to $\chi_S = 1$, reflecting the risk weight applied in Basel II, $\chi_{BL} = 0.2$ that reflects the actual one for OECD countries (Bluhm et al., 2014), $\chi_L = 1$, reflecting the one for retail exposures[5]. Intuitively, there is no cash in the denominator, as banks do not need to hold capital for perfectly liquid asset holding.

Accordingly, the capital requirement binds a bank to have an equity ratio higher than the minimum γ_{min} set by the regulating authority:

$$\gamma_i \geq \gamma_{min} \tag{5}$$

with γ_{min} being the regulatory capital requirement; it is a common given value and it is set to 8% in the baseline model.

Liquidity Requirement - [LqR] Concerning the Liquidity Requirement, we assume that there is a Regulatory Liquidity Buffer, constraining a bank to hold liquid assets for an amount that corresponds to at least α_{min}% of the Deposits. Additionally, each bank has also an "appetite for liquidity", β^i, that is exogenously distributed following a $\beta(2, 40)$ distribution (with $\mu = 0.0476$ and $\sigma = 0.0325$), that instead determines the discretionary liquidity buffer that each bank decides to have.

The parameter α_{min} is imposed by the regulating authority and needs to be met; while β^i is self-imposed, thus the corresponding discretionary liquidity buffer can be eroded or used when the bank needs it or sees profitable market occasions. If a bank can use up its extra liquidity buffer, going below the self imposed constraint, it cannot make use of the regulatory liquidity buffer. Moreover if a bank has borrowed on the IBLM, it will hold the same percentage of precautionary asset of a comparable liquidity class, i.e. equally or more liquid, BL or C.

Having defined $\alpha_i = \frac{C^i}{D^i}$, the liquidity constraint imposes that $C^i \geq \alpha_{min} \cdot D^i$.

$$\alpha_i \geq \alpha_{min} \tag{6}$$

$$\text{or} \quad C^i \geq \alpha_{min} D^i \tag{7}$$

while it will self-impose the following discretionary constraints:

$$\begin{aligned}\text{Liquid Assets} &\geq (\alpha_{min} + \beta^i) \cdot \text{Deposits} \\ C^i &\geq (\alpha_{min} + \beta^i) \cdot D^i\end{aligned} \tag{8}$$

and

$$C^i + BL^i \geq (\alpha_{min} + \beta^i)(D^i + BB^i) \tag{9}$$

Therefore, a bank will choose the optimal amounts of bank lending, securities, and bank borrowing that maximizes the expected profits,

$$\max_{BL^i, BB^i, C^i, S^i} \mathbb{E}(\pi^i) = r^{rf} \cdot BL^i + \frac{r_i^s}{p^{mkt}} \cdot S^i - r^{rf} \frac{1}{1 - \xi PD^i} \cdot BB^i \tag{10}$$

subject to the balance sheet structural constraint (Eq.3 and Eq.2), the regulatory constraints (Eq.15 and eq.6), and the discretionary constraint (Eq.8 and Eq.9)

Moreover, for completeness of the model,

$$C^i \geq 0; \qquad BL^i \geq 0; \qquad BB^i \geq 0; \qquad S^i \geq 0$$

[5] `http://www.bis.org/bcbs/publ/d347.pdf`

3.1.2 Asset manager optimisation problem

Asset managers, m, maximize their profits π^m

$$\max_{C^m, S^m} \pi^m = \frac{r^s_m}{p^{mkt}} \cdot S^m \tag{11}$$

subject only to a fully discretional liquidity constraint: being exposed to redemptions risks, asset managers emulate banks' example and self-imposed a precautionary liquidity buffer in case of participations redemption.[6]

$$C^m \geq (\alpha_{min} + \beta^m) P^m \tag{12}$$

Moreover:

$$C^m \geq 0; \qquad S^m \geq 0$$
$$C^m + S^m = P^m$$

3.2 Equilibrium

Determining the r^{rf} and the equilibrium on the interbank lending market. Since only banks take part to the interbank lending market, let us define BL^{ij} as the liquidity lending of bank i to bank j, and BB^{ij} as the liquidity borrowing of bank i from bank j; then $BL^{ij} = BB^{ji}$. Furthermore, as a bank i can lend to more than one bank and, conversely, borrow from more than one bank, let us also define

$BL^i = \sum_{k=1}^{N_B} BL^{ik}$ as bank i's total lending to all other banks

$BB^i = \sum_{k=1}^{N_B} BB^{ik}$ as bank i's total borrowing from all other banks

As in Bluhm et al. (2014), to find the clearing price on the interbanking lending market, banks first evaluate their optimal amounts of BL^i or BB^i for the given initial value of r^{rf}, then a central auctioneer sums them up and determines the aggregate supply and demand of liquidity on the interbank lending market:

$$F^{supply} = \sum_i BL^i$$

$$F^{demand} = \sum_i BB^i$$

; and

- if $F^{supply} < F^{demand} \Rightarrow r^{rf}$ is increased and $r^{rf}_{new} = \frac{r^{rf}_{old} + \overline{r}^{rf}}{2}$
- if $F^{supply} > F^{demand} \Rightarrow r^{rf}$ is decreased and $r^{rf}_{new} = \frac{r^{rf}_{old} + \underline{r}^{rf}}{2}$

with $\underline{r}^{rf}$ and $\overline{r}^{rf}$ being the lower and upper bound of the interval of values that r^{rf} can take, i.e. $r^{rf} \in [\underline{r}^{rf}, \overline{r}^{rf}]$.

The price tâtonnement stops when the value of the excess demand is minimized. [7]

Given this setting, banks will choose their optimal portfolios depending on the relative values of the cost of borrowing money from other banks $r^{rf} \frac{1}{1-\xi PD^i}$, the returns on money lending r^{rf} and the returns on the security r^s. Keeping in mind that the heterogeneity of probabilities of default implicates that banks have different costs of borrowing money (riskier banks will pay higher interest for borrowing) and that the cost of borrowing money on the interbank lending market is higher than the expected return of lending money to other banks (since both PD and ξ are < 1), we can distinguish three categories of banks:

Lenders: for which $r^s < r^{rf} < r^{rf} \frac{1}{1-\xi PD^i}$

when the security is less profitable than lending in the IBLM, banks will keep the least regulatory cash, and try to lend the remaining available liquidity;

Investors: for which $r^{rf} < r^s < r^{rf} \frac{1}{1-\xi PD^i}$

when the security is more rewarding than lending to other banks but borrowing costs are higher than the returns on the security, banks will keep the least regulatory cash, will borrow no money from other banks (since it is too expensive) and invest the rest in security;

[6] See Morris et al. (2017) about the empirical evidence.

[7] In this framework, we minimize excess demand which – because of a discrete number of banks – may not reach zero; nevertheless as the total number of banks increases, the excess demand converges asymptotically to zeros.

Mixed Portfolios: for which $r^{rf} < r^{rf}\frac{1}{1-\xi PD^i} < r^s$
when the security return is larger than the cost of borrowing money, banks will borrow money in the IBLM to invest it in the security, they will keep the least regulatory cash and the least discretionary Bank Lending to compensate the bank borrowing with an asset of the same liquidity class.

These three business models characterize the level of interaction among the financial institution.

The emergence of the bank network Once the clearing price r^{rf} in the IBLM is set, banks need to be matched to clear the market.

Banks are matched randomly and they exchange

$$BL^{ij} := min\{BL^i, BB^j\}$$

.

If $(BL^i - BB^j) > 0$, i.e. if bank i has residual liquidity to lend, bank j becomes inactive and bank i stays active on the interbank lending queue with its residual liquidity supply; the opposite happens if $(BL^i - BB^j) < 0$. The transactions take place as long as there are active banks in the queues; when either the supply or the demand queue has no active bank left, the market is closed and (almost-)cleared at the almost-equilibrium risk-free return r^{rf} that minimizes the excess demand. Banks that remained with unsatisfied supply (demand) due to the imperfect market clearing, re-adjust their investment portfolios, subject to the amounts of BB/BL they could access on the interbank lending market.

This way, through interbank lending, a network among banks is created. The graph (N_B, g) consists of the set of N_B nodes (the banks) and a real valued $N_B \times N_B$ adjacency matrix g, where the entry g^{ij} represents the weighted and directed relation between bank i and j, in particular $g^{ij} = BL^{ij}$, and define the existing edges between nodes.

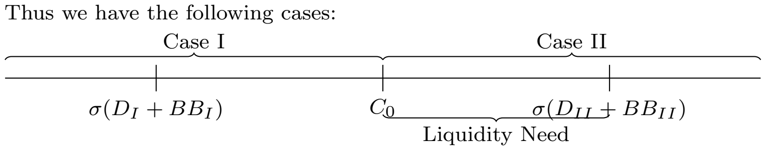
Since asset managers do not have access to the interbank lending market, they are not part of the network, so they do not suffer direct effects, but are affected by indirect effects through the fire-sale.

3.3 Shocks and the model dynamics

Once the system has been initialized and the banks have determined their optimal balance sheet, we simulate an exogenous liquidity shock: a bank i (or an asset manager m) is subject to an initial shock.

A **liquidity shock** has magnitude $\sigma \in [0, 0.5]$ and its entity is $\sigma \cdot (D^i + BB^i)$; clearly the shock does not exceed the total value of "non-sticky" assets but can indeed exceed the usable liquidity buffer to face the liquidity shock (i.e. Cash).

Thus we have the following cases:



Case I: $\sigma(D_0 + BB_0) \leq C_0$ If the liquidity shock is smaller than the available liquidity, the bank simply pays out the corresponding liabilities.

Case II: $\sigma(D_0 + BB_0) > (C_0)$ if, on the contrary, the liquidity shock is larger than the available liquidity, then the bank needs more liquidity to cover the shock.
To face the liquidity shock, the Bank $\bar{i}$ will need the extra amount λ^i:
$\lambda^i = \sigma(D_0^i + BB_0^i) - C_0^i$

Therefore

$$\lambda^i = \begin{cases} \sigma(D_0^i + BB_0^i) - C_0^i & \text{if} \quad C_0^i \leq \sigma(D_0^i + BB_0^i) \\ 0 & \text{otherwise} \end{cases}$$

We assume that bank lending is perfectly liquid, can be called back with no discount and a lender can decide not to roll over the debt and get the money back, given that the corresponding Borrower has enough liquidity to pay back the borrowed amount; differently, the security is not fully liquid and can be sold on the market any time, but a discounted price due to the urgency of the sale. Unlike Greenwood et al. (2015), we do not assume that banks disinvest proportionally to their portfolio holdings, but they will follow a pecking order determined by the liquidity class of the assets and subject to the availability of the different assets in their portfolios:

• *Use Cash* : first they exhaust all their Cash;

• *Call Back BL* : if cash is not enough, the bank *calls back* its interBank Lending (if any), for the needed amount, proportionally to the initial total lending to the specific banks, and regardless whether it is more or less profitable than the security;

• *Sell the Security* : if the lending paid pack are still not enough to face the shock, the bank proceeds to a sale of security at a fire-saled price, as it is illiquid.

Whenever a bank needs liquidity, it determines the amount of bank lending to call back, and -in case- the total value of S to sell.

If a bank does not manage to face the liquidity shock even after selling the security, it goes bankrupt; otherwise it proceeds and it will undergo the periodical check of the regulatory requirements.

If any of the two[8] is not met, the bank determines the necessary disinvestments to "rebuild" a proper liquidity or capital regulatory buffer, and repeats the same cycle of actions: first call back Bank Lending, then sell the security. Successively, it checks once again the requirements and if they are not met, the bank defaults, in which case its exposures are updated on its counterparts' balance sheets according to the loss given default parameter. We assume that banks, in time of distress, simply proceed with passive portfolio management.

Ergo, there is a threshold that triggers movements on the market following the initial shock, and if we define $\alpha_0^i = \frac{C_0^i}{D_0^i}$ as the actual total liquidity buffer that bank i holds at $t = 0$, this critical loss amounts to

$$\sigma^{i*}(D_0^i + BB_0^i) = D_0^i \cdot (\alpha_0^i - \alpha_{min}) + \sigma\alpha_{min}D_0^i$$

$$\sigma^{i*} = \frac{(\alpha_0^i - \alpha_{min})D_0^i}{(1-\alpha_{min})D_0^i + BB_0^i}$$

Due to the marked-to-market security,

A decrease in the market price affects both banks and shadow banks. a price drop causes a variation in the book value of Security and Equity, that implies a change of equity ratio for Banks, and a potential trigger of **redemption** for Shadow Banks. Redemption of participations happens because investors, seeing the decrease in the asset value of the asset manager, try to anticipate further losses and decide to "withdraw" or not to renew their participations.

We therefore introduce the idea that the non-liquid security has a fundamental value $\overline{f}$, and both banks and asset managers $k = i, m$ have individual noisy valuation of it $f^k = \overline{f} + \epsilon^k$, centered in $\overline{f}$ [9].

When the market price is lower than the noisy fundamental value of the security held by an asset manager, a price change generates panic among the *depositors* who will redeem a share of their participations. Redemptions increase exponentially with the percentage change of the price with respect to the previous iteration $\delta = \frac{p^m_{t-1} - p^m_t}{p^m_{t-1}}$.

$$\text{redemption} = \mathbb{1}_{\{p^m < f^m\}} P^m \cdot \frac{exp(\eta\delta) - 1}{exp - 1}$$

. When the asset manger faces a redemption, it will be faced in the same fashion of liquidity shock: use cash to reimburse participations first, and in a second moment -if needed- fire-sale the security for the corresponding needs ($N_m^S = redemption$); in case the latter is not enough to absorb the redemption, the asset manager will exit the market. As we are interested in the downward dynamics of the fire-sale, and since the time span simulated is relatively limited (50 iterations of interaction) we need to specify that for the baseline setup we do not account for potential price recovery of the non-liquid asset.

3.4 Sequence of the contagion process

At any time a bank might need to take action to face the different needs arising from the interaction with the financial system; therefore each bank i might need to determine the amount λ_i it needs, to pay the liabilities called back by other banks ($BB_c^{ij} alledback$) or withdrawn by depositors. At time 0, only the bank hit by the exogenous shock needs to determine $\lambda_i = max\{\sigma(D^i + BB^i) - C^i, 0\}$; while in later iterations, λ_i for a generic i is

$$\lambda_i = \sum_j \{(BB^{ij}_{calledback})\} \tag{13}$$

[8]Banks check the two regulatory requirements: 1.$C_i \leq \alpha_{min}D_i$, and 2.(Total Equity/RWA) $\leq \gamma_{min}$

[9]In our case we set $\epsilon \sim N(0, 0.1)$

to meet liquidity requirement

$$\nu_i^{Liq} = max\{0, \alpha_{min} D_i - C_i\} \quad (14)$$

or to disinvest and meet the capital requirement

$$\nu_i^{Cap} = max \left\{ 0, \frac{\gamma_{min} \cdot RWA_i - Equity_i}{\gamma_{min}} \right\} \quad (15)$$

BL callback. Once banks have determined these amounts, they know the portion of BL they need to recover,

$$N_i^{BL} = min\{max\{\lambda_i + \nu_i^{Liq}, \nu_i^{Cap|BL}\}, BL_i\} \quad (16)$$

where $\nu_i^{Cap|BL}$ is the amount of BL that needs to be called back to meet the capital requirements and

$$\nu_i^{Cap|BL} = \frac{\nu_i^{Cap}}{\chi_{BL}}$$

N_i^{BL} is called them (proportionally) from all the banks $j's$ which borrowed money from bank i; the amount of BB-askedback will be, in turn, considered by banks $j's$ as a liquidity shock, and will be treated similarly to the initial one, i.e. using first cash, then determining their own need of BL-callback, and the quantity of non-liquid asset to be sold. Moreover, if two banks are mutually exposed and they are both trying to disinvest, they are allowed to cancel the mutual exposure.

This is the first channel of propagation of the shock.

NLA sale.

Who Sells: The Supply. After calling back bank lending, banks update their needs and determine the new values of λ_i, ν_i^{Liq}, and the disinvestment of the security to meet the capital requirement

$$\nu_i^{Cap|S} = \frac{\gamma_{min} \cdot RWA_i - E_i}{\gamma_{min} \chi_S}$$

. It follows that the total *value* of security to be sold by bank i is

$$N_i^S = min\{max\{\lambda_i + \nu_i^{Liq}, \nu_i^{Cap|S}\}, S_i\}$$

Since any time the market opens, banks and shadow banks first try to sell at $p' = p^m - \epsilon$, we further define $q_{s,i}$ and $q_{s,m}$ as the amount of nla that bank i and shadow bank m respectively need to sell

$$q_{s,i} = min \left\{ nla^i, \frac{N_i^S}{p'} \right\}$$

$$q_{s,m} = min \left\{ nla^m, \frac{N_m^S}{p'} \right\}$$

.

Then the sum of individual supplies of nla in the market gives the aggregate supply

$$Q_S = \sum_i q_{s,i} + \sum_m q_{s,m}$$

It follows that the supply includes three kinds of selling agents: a) banks in liquidity shortage due to either a direct exogenous liquidity shock or a shock on the IBLM; b) banks that need to disinvest to meet the requirements; c) asset managers that need to sell to face redemption.

If a bank realizes that even the sale of the entire security portfolio would not be enough to face liquidity shortage, it withdraws from the market due to under-capitalization.

Who Buys: The Demand. When the market for the security is open, i.e. when there is at least a bank or an asset manger that needs to sell the non-liquid assets, every bank and asset manager can buy at two conditions: it has to be *profitable* and *feasible*.

The investment is said to be *profitable* for bank k when the market price is lower than its personal valuation $p' < f^k$; while it is *feasible* if the institution has liquidity ready to be used: an asset manager can use up all its cash, but a bank can deplete only the extra liquidity buffer within the limits posed by the capital requirement. It follows that an institution either sells or buys: a bank that sells *nla* does so due to a liquidity shortage; consequently, buying would not be feasible. Aggregate demand for the Security when the market opens is calculated in the following way:

- A *Bank* demand of non liquid asset $q_{d,i}$ -given it is profitable- needs to satisfy

$$q_{d,i} \leq \frac{C^i - \alpha_{min}(D^i) - \sum_j BB^{ij}_{askedback}}{p'}$$

  and

$$q_{d,i} \leq \frac{\text{Equity}^i - \gamma_{min}\text{RWA}^i}{(\gamma_{min}\chi_S - 1)p'}$$

- while a *Asset manager* demand of non-liquid asset is

$$q_{d,m} = \frac{C^m - redemption^m}{p'}$$

The aggregate demand of the non-liquid asset for price p', instead, is given by

$$\begin{aligned} Q_D &= Q_{D,B} + Q_{D,AM} \\ &= \sum_i^{N_B} \mathbb{1}_{\{p'<f^i\}} q_{d,i} + \sum_m^{N_{AM}} \mathbb{1}_{\{p'<f^m\}} q_{d,m} \end{aligned} \tag{17}$$

If the market opens and there is positive demand for the security at price p', exchange takes place, banks update their liquidity needs given the new market price. If they are still in liquidity shortage or need to disinvest more, they lower again the price and set it to $p'' = p' - \epsilon$, for which the corresponding new demand is determined and, if positive, more exchange at the new price takes place. The process iterates until either the supply is fully exhausted or the market price for the security has dropped to zero.

If supply is smaller than demand, buyers buy proportionally to their demand with respect to aggregate demands, i.e. each B/AM k will buy

$$q^*_k = \frac{q_{d,k}(p^*)}{Q_D(p^*)} \cdot Q_S(p^*)$$

When the market closes, the last price p^* becomes the new market price, all banks and asset managers update balance sheets with the new quantities of bought securities, and update the book value of the marked to market Security (held to trade and not to maturity) and the Equity value. Banks will then proceed in the periodical requirements checks.

4 Results

We use simulation techniques to explore the market dynamics implied by the model, in particular the evolution of balance sheets of the agents. We simulate for 100 different seeds, nine possible settings of the environment determined by the combinations of (α_{min}, γ_{min}), i.e. the liquidity and capital requirement parameter respectively, and we let α_{min} vary in $\{8\%, 10\%, 12\%\}$, while γ_{min} in $\{6\%, 8\%, 10\%\}$. The model runs for 50 "days", during which banks and shadow banks react to the movements of the interbank lending market and the changes of the security price. We simulate a system with 60 banks and 40 asset managers and we report the number of undercapitalised banks in each of the periods. For each of these settings both banks and asset managers -each institution one by one- is subject to liquidity shocks with 26 shocks of different magnitude. We investigate how the initial exogenous and idiosyncratic shock spreads through the system and its cascade effects on prices, shares of undercapitalised banks and the speed of contagion.

We have selected and investigated a few representative simulations to illustrate what happens to the banking system when hit by different shocks. In the x-axis (of Fig.1 and Fig.2) we have the absolute value of the shock (in order to grasp the entity of the shock with respect to the total volume of the market), and on the y-axis there is the number of undercapitalised banks at a specific point in time. An increase in capital requirement (i.e. on the equity ratio) puts a cap on the risky investments, it limits the exposure to possible contagion and, on the other hand, it decreases the incentives to borrow to increase leverage. As a result, higher capital requirements create an excess supply of money of the IBLM that depresses the risk-free return rate determined through tâtonnement process, this limited demand of bank borrowing together with a lower risk-free return rate on money lending make the alternative investment into the non-liquid security more appealing. Even if the volumes of the security are not higher, the relative volume of the riskier asset on the market increases.

Moreover, since higher capital requirements tighten the bank borrowing amount and given that the liquidity shock is defined as a percentage of liabilities, smaller balance sheets imply smaller initial shocks in absolute terms: this explains why for higher γ's lower values of initial shocks are observed (see x-axis in Fig.1 and Fig.2).

To illustrate the evolution of contagion the following figures show the number of undercapitalised banks after 25 and 50 days of simulations, for shock originating in the banking sector or in the asset manger sector (blue and orange circles, respectively).

- **Speed of Contagion** When the shock is originated in the shadow bank sector (orange dots), the system stabilizes already after 25 days, in two possible "equilibria": for a relatively large shock, all banks fail; while for relatively small values of the exogenous shock, either no bank fails or all of them do. [10]

  While the system seem to ultimately reach the same equilibrium conditions, when the shock originates in the banking sector it takes longer for the system to reach the equilibrium. This is precisely due to the contagion process described above: a shadow bank that firesales affects both banks with security holdings only and banks with mixed-portfolios that, in turn, affect banks active exclusively in the IBLM. On the other hand, a bank might affect the other banks by calling back inter-bank lending but it will take longer to reach them all through this channel, or to trigger a fire-sale in a second moment.

  Moreover, at a first glance, it seems that tighter capital requirements (moving to the right across columns in Fig.1) accelerates the cascade dynamics of failures, and after 25 iterations there are fewer cases that have not stabilized yet in one of the two "steady states".

- The other interesting element is that the same *small* values of initial exogenous shock will more often lead the system to the entire collapse when the shock originates in the banking sector, rather than in the shadow bank word. Relatively small shocks can be absorbed by asset managers, thanks to their flexibility due to the lack of regulatory constraints (in Fig.2. For small initial shocks originated in the asset manger sector, the number of undercapitalized banks – the orange marker – is always equal zero; on the contrary, when originated in the banking system, the shock of the same size may lead to a fire-sale).

[10] Replicated for other seeds of the simulation, the result is robust.

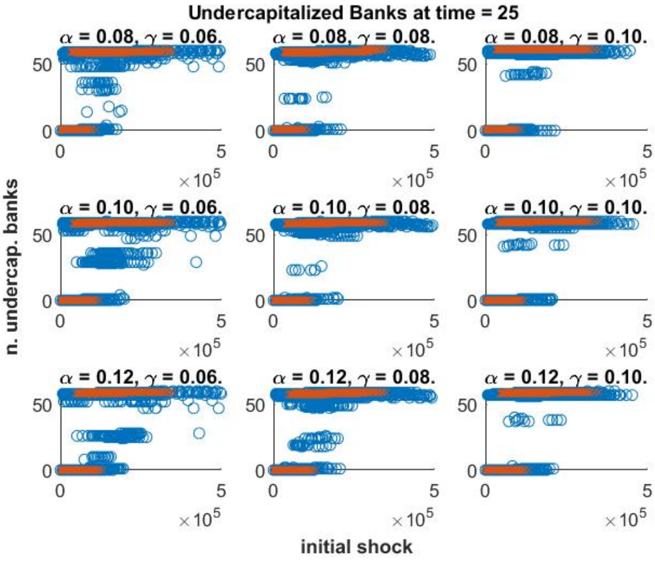


Figure 1: Undercapitalised banks at day 25

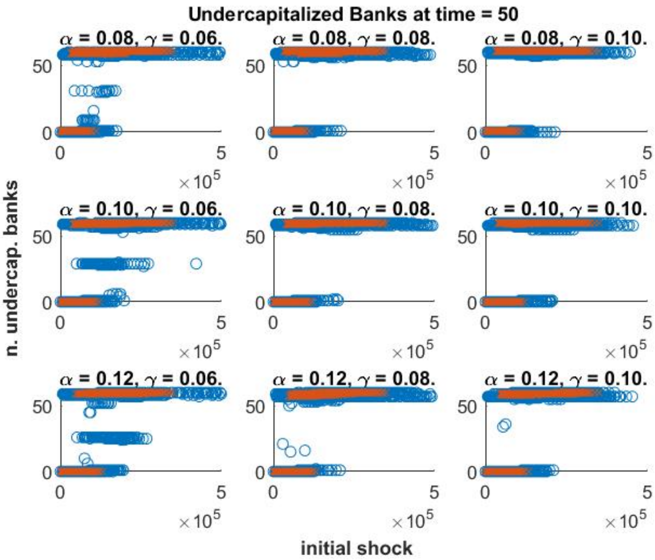


Figure 2: Undercapitalised banks at day 50

Note: x-axis: shock value; y-axis: number of undercapitalised banks when the shock originated in the banking sector (blue dots), or in the asset manger sector (orange dots)

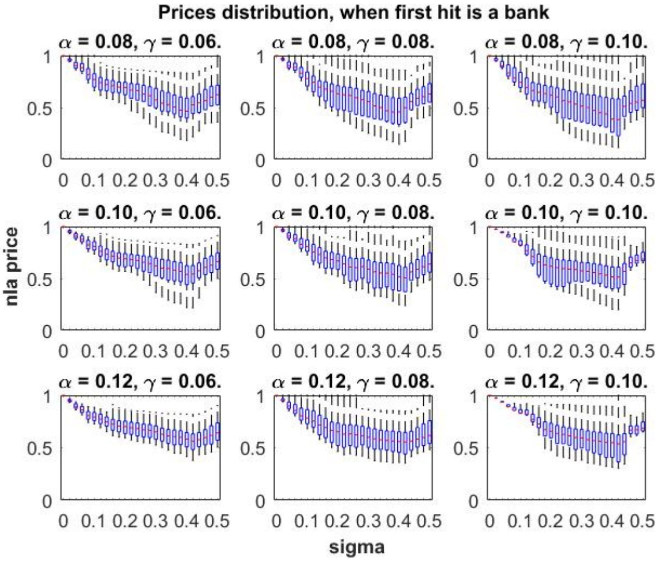


Figure 3: Price distribution: Boxplots for a random seed (seed = 1)

Note: Price distribution across time, when the initial shock hits a bank. x-axis: sigma (i.e. shock intensity, as a percentage of (Deposits+BankBorrowings)); y-axis: security price.

The boxplots in Fig.3 depicts how quickly the price decreases and much it can drop: each boxplot plots the distribution of the price during the 50 "days" of simulation; the median corresponds to the 25th day of simulation. The price seems to stabilize within the first half of the simulation period.

Correspondingly, we plot the distributions of the shares of failed banks for the same simulations (always across time and when the shock originates in the banking sector, see Fig.4). The system reaches a "steady state" relatively quickly; the larger the entity of the shock with respect to the individual liabilities, the larger the final share of failed banks. For this specific simulation (which is representative of all others) we observe a faster convergence to the steady (failure) state for larger values of capital requirements.

For shocks originating in the asset manger sector (see Fig. 5 and Fig.6 for price dynamics and the share of undercapitalised banks respectively), no fire-sale is triggered for small shocks since the shock can be faced with agents' own liquidity buffers. The difference in outcomes between traditional banks and asset managers is given by the fact that, after having used the liquidity buffers, the first group needs to re-adjust the balance sheet to meet the requirements, while the latter does not, so – up to their liquidity buffer – they do not need to fire-sale the security. But as soon as asset managers trigger the fire-sale and the price starts to decrease, banks join the fire-sale and add to the distress in the market. Although for higher capital requirements the price does not drop as much as for lower capital requirements, the effect on the depletion of banks' capital is equally intense and fast.

Averaging the results over all simulations, in Fig.7 and Fig.8 we plot the average final share of undercapitalized banks (solid line) and the market price of the security (dotted line) for each intensity σ of the initial shock. Intuitively, bigger initial shocks correspond to lower fire-sale price and more undercapitalized institutions.

We find that the asset manager sector, which is not constrained by the regulations, is able to better absorb relatively small shocks that originated in that same sector, as they provide flexible liquidity in the market to partially embank the fire-sale. Nevertheless, when the initial redemption is big enough to force a security sale, the decrease in price will also affect all banks investing in the security in the second round and, in the third round, also those active exclusively in the interbank lending market. This channel of contagion works because banks with mixed portfolios, i.e. investing in both bank lending and security, act as plague spreader, being in the position to not only spread the shock to both sectors, but also to receive the shock from one sector and propagate it to the other. This supports the intuition that highly interconnected banks are systemically important, as they could spread the shock widely across the financial system.

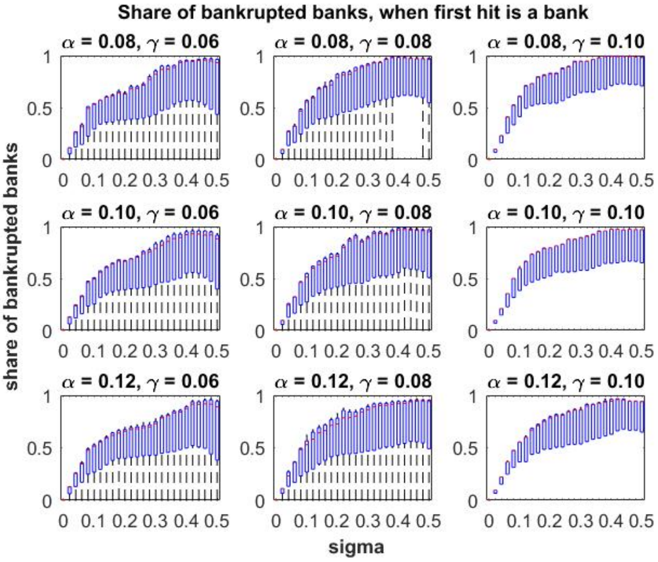


Figure 4: Share of undercapitalised banks: Boxplots for a random seed (seed = 1)

Note: Share of bankrupted banks across time, when the initial shock originates in the banking sector. x-axis: sigma (i.e. shock intensity, as a percentage of (Deposits+BankBorrowings)); y-axis: share of undercapitalised banks.

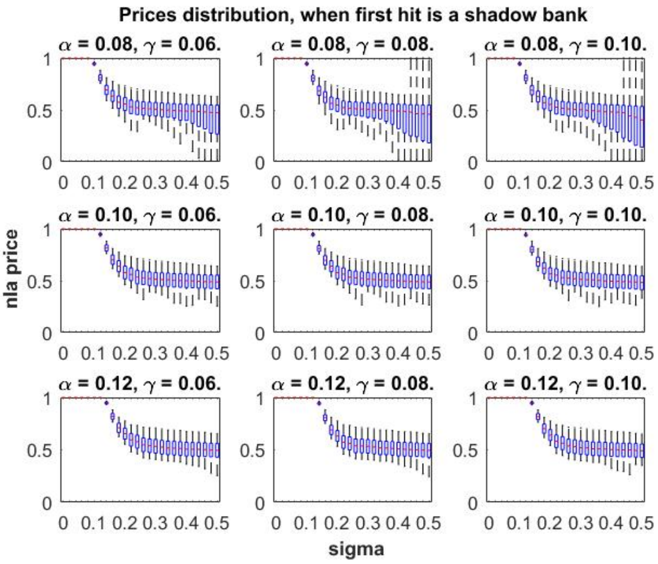


Figure 5: Price distribution: Boxplots for a random seed (seed = 1)

Note: Price distribution across time, when the shock originates in the asset manager sector. x-axis: sigma (i.e. shock intensity, as a percentage of (Deposits+BankBorrowings)); y-axis: security price.

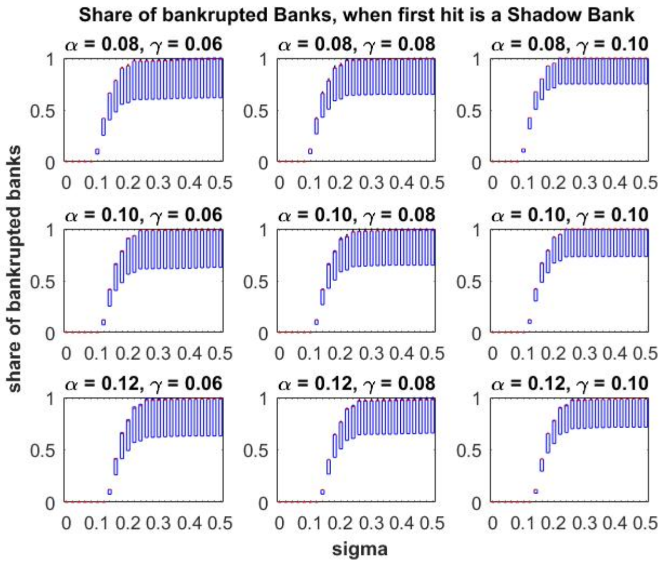


Figure 6: Share of undercapitalised banks: Boxplots for a random seed (seed = 1)
Note: Share of bankrupted banks across time, when the shock originates in the asset manager sector. x-axis: sigma (i.e. shock intensity, as a percentage of (Deposits+BankBorrowings)); y-axis: share of undercapitalised banks.

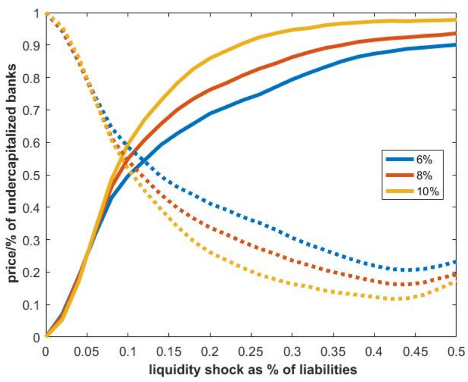


Figure 7: shock originates in the banking sector

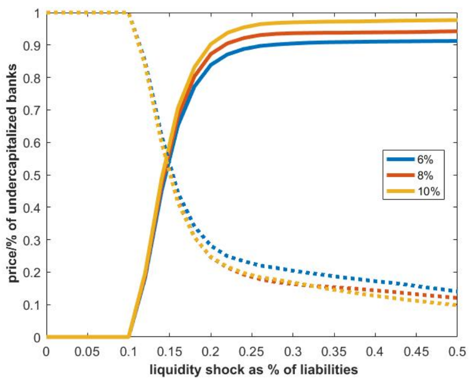


Figure 8: shock originates in the asset manager sector

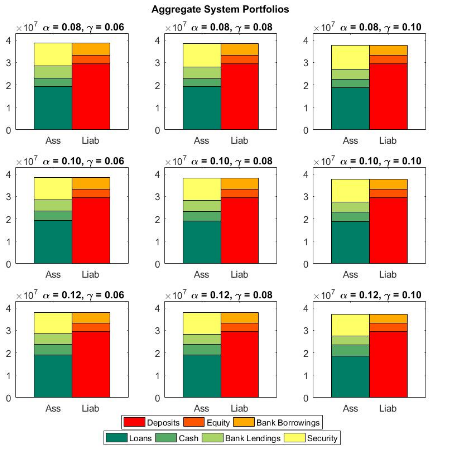


Figure 9: Aggregate system-wide portfolios

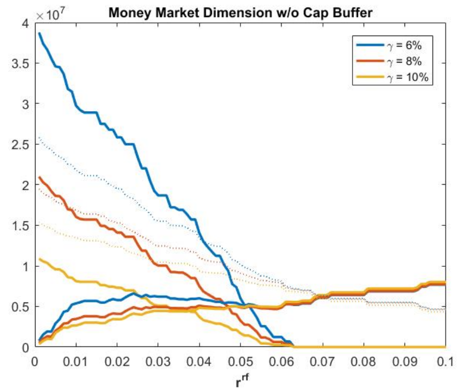


Figure 10: IBML-Market and Risk-free Return Rates. $C^i + BL^i \geq (\alpha_{min} + \beta^i)(D^i + BB^i)$

Finally, we find that an increase in the minimum capital requirement might exacerbate the contagion (yellow line in Fig.7). The underlying dynamics involves the structure of the interbank lending market: higher capital requirement imposes a cap on risky security investments, thus also limiting profitable leverage opportunities for banks who were borrowing money to be later invested in the security; thus a decrease in the money demand (see Fig.10), paired with an almost unchanged money supply implies a lower risk free rate of return on money lending. Since the heterogeneous returns on the security are given, a lower risk free return rate might change the profitability incentives: banks that were previously only holding BL, may now turn to the relatively more profitable security; banks who were only investing in the security, may want to borrow to reinvest (since the cost of borrowing has decreased), and mixed portfolio banks may opt to borrow more.

As a result, more banks choose a mixed portfolio investment strategy (see Fig.11). Although these changes in investments and business models always take place within the limits imposed by the capital constraint, the capital buffers (i.e. the amounts of capital held in addition to the capital requirements) are strongly affected due to the investment opportunities: as a matter of fact, banks investing only in bank lending are the ones (self-)endowed with highest capital buffers, followed by those investing only in the security; while banks with mixed portfolios prefer to exploit all the capital flexibility they have, thus keeping only regulatory capital and almost no capital buffers (see Fig.12). The increase in capital requirement creates incentives for more banks to follow a mixed portfolio strategy and, as a result, keep less excess voluntary capital. This not only makes business models more homogeneous and thus reinforces the asset price channel of contagion, but also increases the likelihood of falling below the minimum regulatory capital threshold, which in turn facilitates the contagion. This dynamics goes hand in hand with the increasing rigidity of banks that are now both less able to absorb the initial shocks due to smaller excess buffers and less likely to act as buyers of risky asset in order to cushion the fire-sale.

5 Conclusions

We have built a framework that attempts to capture the interactions between two kind of agents, namely traditional banks and asset managers, in a setting where all institutions are indirectly connected through holdings of similar securities, while traditional banks are also interlinked via interbank lending. These two channels determine the dynamics of contagion and, as we demonstrated in the simulations, in extreme liquidity stress may lead to a fire-sale of the asset and to the collapse of the entire system.

In our model banks are constrained in their portfolio choice, as they are required to comply with Basel III-like regulatory requirements. We investigate the role of liquidity and capital requirements in determining the price dynamics, speed and extent of contagion.

Within the limits posed by the usual but necessary simplification to squeeze reality into theory, we find evidence of the important role that banks with mixed portfolios play in propagation of contagion.

First, when the initial plague-spreader bank has interbank claims on its balance sheet, it will start a chain of

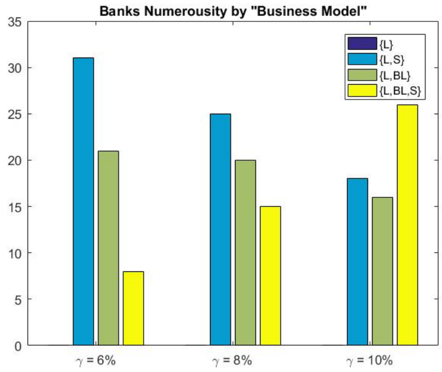


Figure 11: Number of Banks by Business Model, for each level of regulatory requirement (γ)

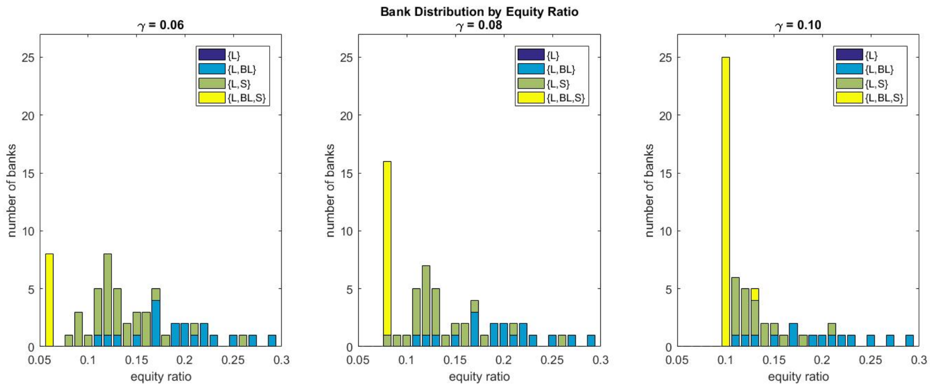


Figure 12: Number of banks by actual equity ratio

withdrawals which can lead to a fire-sale. Instead, if either the shock is absorbed by the system or if it happens that banks involved in the recalls do not hold the security on their balance sheets, a fire-sale can be mitigated and the incidental contagion will involve only a limited group of banks — precisely those connected through the interbank lending.

On the contrary, when the initial plague-spreader holds on its balance sheet only a non-liquid security, a fire-sale is inevitable and the contagion will affect all the other banks with similar balance sheet characteristics. The connection between the two sub-systems, i.e. the link that has a potential to adversely affect the entire system, is established by those banks with mixed portfolios that, when facing a security price drop, mat decide to call back their interbank claims. Subsequently, other banks may need to call back their own claims, too, and, if this is not sufficient, then fire-sale the non-liquid asset.

It follows that when the liquidity shock is experienced by an interbank claims holder, there are chances that it strands on the shores of the interbank lending market and may not spillover to other segments of the financial markets through the ferry-banks with mixed portfolios. Conversely, when the shock hits a security-only holder it will automatically affect all security holders, the ferry-banks – if forced to adjust their balance sheets due to regulatory constraints – will transmit the shock to the interbank market. This mechanism explains why, in our setting, shocks originating among shadow banks tend to spread and affect the banking system quicker than those originating in the banking sector and spreading to the shadow bank sector. In other words, the speed of contagion may be related to the direction in which the shock is being channelled across the financial system.

Second, capital requirements may have perverse implications on the stability of the entire system. While higher capital requirements enhance the resilience of individual banks, they also make the bank balance sheet look alike. Banks are optimising their portfolios according to the risk-return principle. Initially banks have incentive to keep less risky assets, i.e. the interbank lending, which do not require holding as much capital as more risky assets, i.e. the non-liquid asset. However, this leads to an excess supply of interbank claims and drives down the risk free return rate of bank lending that, as a consequence, becomes a less appealing investment for banks. There is a trade-off: on the one hand the increase in capital requirement lowers the total volume of the interbank lending market; on the other hand, the lower risk free return rate implies lower interbank borrowing costs, thus creating enough margin to borrow money to be invested in the riskier investment, thus generating the need—due to the initial liquidity constraint—to hold a corresponding minimum amount of interbank lending. The relative dimension of interbank lending market with respect to that of the riskier and less liquid security decrease, and the number of banks with mixed portfolios increases. This homologation of business models together with a higher (involuntary) exposure the the non-liquid security are reflected in a faster and more extreme consequences of a liquidity shock at the system level.

Third, asset managers could act as shock absorbers but only for a relatively small shocks and when they have excess liquidity. Small liquidity shocks originating in the asset manager sector are absorbed because these institutions do not need to re-adjust their balance sheets to meet the regulatory requirements and hence are flexible in using their excess liquidity buffers to cushion the shocks.

Future work may be needed to better understand the two trade-offs we identified. First, higher capital requirements may increase the resilience of the entire system by strengthening the capital position of individual banks but at the same time it may enhance contagion by homogenising banks' balance sheets. Second, while non-regulated shadow banks may incentivise contagion and exacerbate fire-sales, they can also provide flexible buffers and absorb the adverse effects of small liquidity shocks.

Policy and regulation, like a mother with her child, should aim at the right balance between control and freedom, in the search for stability and growth.

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Appendix A
Profit Function Derivation

Bank i's profit maximization problem is given by

$$\max_{BL^i, BB^i, C^i, S^i} \mathbb{E}(\pi^i) = \max_{BL^i, BB^i, C^i, S^i} \mathbb{E}(\pi^{lending_i}) + \mathbb{E}(\pi^{investing_i}) - \mathbb{E}(cost^{borrowing_i}) \tag{18}$$

where $\mathbb{E}(\pi^{lending_i})$ are the expected profits coming from the lending activity of bank i to other banks (BL^i), $\mathbb{E}(\pi^{investing_i})$ are the expected profits of investing S^i in the non liquid asset, and $\mathbb{E}(cost^{borrowing_i})$ is the cost of borrowing money (BB^i) from other banks. Although the profits should include also the return on loans (L^i), together with the cost of equity (E^i) and deposits (D^i), these are not included in the maximization problem since loans are sticky and cannot be disposed of and capital and deposits are bank specific structural characteristics and are exogenously given; therefore these variables do not enter the maximization problem.

Interbank Lending. Considering the Interbank Lending Market, if bank i lends BL^{ij} to bank j, the first will charge a price of $(r^{rf} + r^{PD_j})$ to bank j for the corresponding amount, where r^{rf} is the risk-free return rate charged solely for the transfer of funds from one bank t the other, while r^{PD_j} is internalizing the probability that the borrowing bank j will default.

Therefore the profits deriving from lending BL^{ij} are given by

$$\mathbb{E}(\pi^{lending^{ij}}) = (1 - PD_j)BL^{ij}(r^{rf} + r^{PD_j}) + PD_j BL^{ij}(1 - \xi)(r^{rf} + r^{PD_j}) \tag{19}$$

where ξ is the Loss Given Default, and PD_j is the probability of default of bank j.
In fact, with probability $(1 - PD_j)$ bank j will pay back the amount borrowed and will also pay the corresponding fees, and with probability PD_j bank j will pay back to bank i only $(1 - \xi)$ of what it should have.

We assume that creditors charge a fair risk premium, which implies that the expected profits in presence of risk (that is when charging r^{PD_j}) is equal to the profits deriving from a risk-free loan.

$$\mathbb{E}(\pi^{lending^i j}) = BL^{ij} r^{rf} \tag{20}$$

Thus, equalizing the previous two equations 19 and 20 and solving for r^{PD_j}, that the risk premium for bank j is given by

$$r^{PD_j} = \frac{\xi PD_j}{1 - \xi PD_j} r^{rf} \tag{21}$$

and -consequently-

$$(r^{rf} + r^{PD_j}) = \frac{r^{rf}}{1 - \xi PD_j} \tag{22}$$

Substituting Eq.23 in Eq.19 and summing over all j's, the expected profits of bank i derived from lending activity to other banks is

$$\mathbb{E}(\pi^{lending^i}) = \sum_j \mathbb{E}(\pi^{lending^{ij}}) = BL^i r^{rf} \tag{23}$$

Investing in Security. The second source of profits for bank i are the returns r^{s_i} on investments S^i in the non liquid asset. The returns are heterogeneous among institutions, and are divided by the current market price of the security, initially set to 1, to take into account the inverse relation between the market price and the yield (e.g. in the case of a bond, having fixed interest rate). In our setting, since banks are not allowed to re-optimize in the short run, this particular specification is not determinant of the system dynamics.

$$\mathbb{E}(\pi^{investing^i}) = \frac{r^{s_i}}{p^{mkt}} S^i \tag{24}$$

Interbank Borrowing. Symmetrically, using Eq.20, the cost of borrowing BB^i on the interbank lending market is given by

$$\mathbb{E}(cost^{borrowing^i}) = \sum_j BB^{ij}(r^{rf} + r^{PD_i}) \tag{25}$$

$$= BB^i(r^{rf} + r^{PD_i}) \tag{26}$$

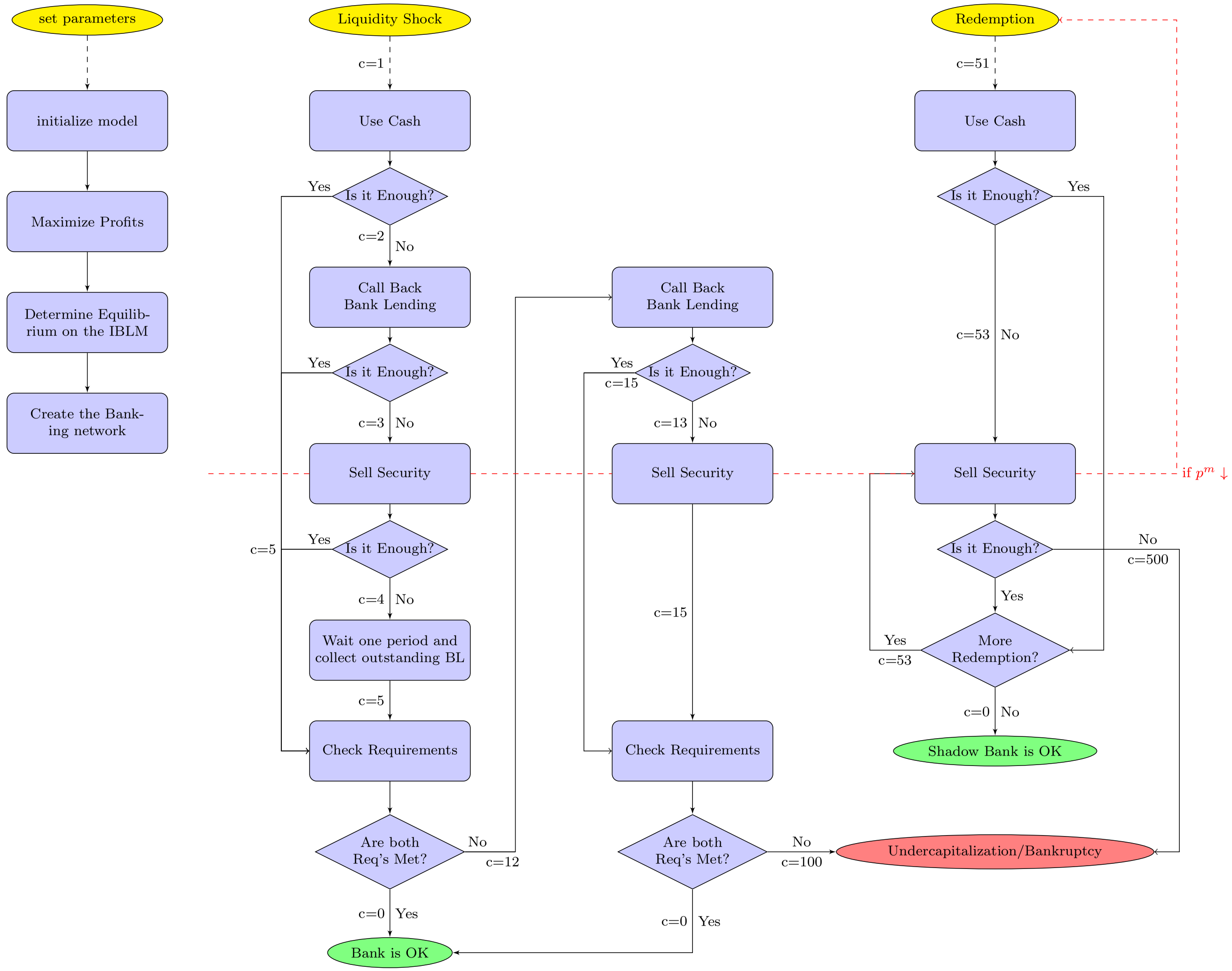
$$= BB^i \frac{r^{rf}}{1 - \xi PD_i} \tag{27}$$

Taken together (Eq.19, Eq.24 and Eq.27), the expected profits of bank i are

$$\mathbb{E}(\pi^i) = r^{rf} BL^i + \frac{r^s}{p^{mkt}} S^i - BB^i \frac{r^{rf}}{1 - \xi PD_i} \tag{28}$$

Appendix B

Flowchart



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