Bilateral netting and systemic liquidity shortages in banking networks

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Bilateral netting and systemic liquidity shortages in banking networks

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Abstract
The cross holding of interbank deposits represents an optimal ex-ante co-insurance arrangement whenever the uncertainty concerning banks’ liquidity needs is idiosyncratic and imperfectly correlated. When a shock to aggregate liquidity demand occurs, however, such an arrangement could be detrimental – depending on the topological structure of interlinkages - as financial exposures become a means to spread risk. If the ex-post facto is an excess demand for liquidity, therefore, regulators could severe potential channels of contagion by forcing banks to net their mutual debt obligations. Starting from these premises we employ simulation techniques with simple interbank structures to obtain two results. First, a state-contingent mandatory policy to bilaterally net mutual interbank exposures comes with a trade-off between the benefits of thwarting the channels of contagion and the harms of a greater concentration of the remaining netted expositions. Second, the balance between the two prongs of the trade-off depends on the metric used by regulators to define financial stability and the topological structure characterizing the interbank market.

JEL codes: C63, D85, G21
Keywords: Interbank markets; Bilateral netting; Systemic liquidity risk

1 Introduction
Due to their peculiar role in the financial plumbing and a vast availability of ready-to-use data, interbank lending markets have recently become a hot topic for theoretical and empirical research. Among the many facets explored
by the literature, the one we select as our starting point is the role of lending and borrowing in interbank markets as a form of liquidity co-insurance. We shall argue that the implications of this theoretical view are conducive to a clear-cut crisis management prescription aimed at curbing a contagion, namely to mandate banks to net their mutual lending exposures on a contingent basis. Exploring the pros and cons of such a proposal is the main goal of this paper.

In doing so, we offer two contributions to the research exploiting numerical simulation techniques to model financial systems as interacting networks. In addition to complement the stream of papers dealing with liquidity cascades (Cifuentes et al., 2005; Gai et al., 2011; Lee, 2013; Chinazzi et al., 2015) by exploring how the bilateral netting of mutual claims affects the resilience of banking systems to funding runs, our work speaks to the choice of the levers regulators can activate in fostering financial stability. While the standard approach in the network literature (Aldasoro et al., 2017; Erol and Ordoñez, 2017) is to analyze how prudential regulation at the level of nodes – through the imposition of capital and liquidity ratios, or the periodic submission of “living will” plans – can implement a safer financial environment by focusing on crisis prevention, we argue that the complementary goal of managing systemic liquidity crisis could be pursued by regulatory tools affecting the structure of links connecting intermediaries among themselves, along the lines discussed by Loepfe et al. (2013) with regards to asset-based overlapping risk exposures.

As shown e.g. in Allen and Gale (2000) and Freixas et al. (2000), by mutually exchanging funds banks may hedge themselves against liquidity shocks arising from uncertainty in the timing or geographical destination of their depositors’ consumption. Provided that the idiosyncratic risks they face are not perfectly correlated, the ex-ante swapping of claims allows banks experiencing liquidity deficits to be funded by banks experiencing liquidity surpluses ex-post. The unpleasant side of the story is that while such an

1 A search on Google Scholar for the keyword “interbank market” limited to the time span following the global freeze of mid-2007 returns more than 23,000 items. We refer the reader to the surveys by Hüser (2015), Glasserman and Young (2016) and Green et al. (2016) for discussions focused on different aspects.


3 An optimal co-insurance scheme can be obtained also in a circular arrangement in which each bank is allowed to make an interbank deposit only in the adjacent bank, so that all relationships are unidirectional. See the incomplete market structure represented in Figure 2 of Allen and Gale (2000). However, note that in this case an interbank market ensures optimal
arrangement turns out to be optimal whenever the total amount of liquidity to be reallocated inside the system is large enough (Castiglionesi and Wagner, 2013), it could prove deleterious when a negative shock to the aggregate demand for liquidity occurs. Interbank deposit exposures can now act as shock transmitters and lead to a spread of losses through contagion-like liquidity cascades over the whole net of lending/borrowing relationships. A major result – corroborated by means of diverse analytical methods – is that in this case the resilience of the system is a function of the topological structure characterizing interconnections. Furthermore, the interaction between the severity of the systemic shock and market connectivity is crucial in determining the ability of the system to resist contagion: for small aggregate shocks higher connectivity helps to restrict the likelihood of default cascades, but for larger shocks the opposite holds true (Ladley, 2013; Cabrales et al., 2017).

A far less explored implication of the co-insurance motive for reciprocal exposures in interbank markets is that once an aggregate liquidity shock has occurred, the ex-ante rationale to exchange deposits may lose significance. As emphasized by Haldane (2009), a sensible approach to avoid contagion is in this case to “hide”. In addition to liquidity hoarding (Gai and Kapadia, 2010; Heider et al., 2015), a possible “hiding” strategy when mutual deposits exist is to net them bilaterally. This helps a safe node to insulate itself from negative spillovers mediated through a withdrawal of the claims infectious banks have deposited in its coffer. Furthermore, bilateral netting should not imply any welfare loss besides that generated by the failure of the institutions originally affected by an exogenous disturbance, given that from a post-shock point of view the reciprocal exchange of deposits is essentially counterproductive.

Starting from these premises, in this paper we study the implications of mandating banks swapping deposits to enter into on-balance-sheet (OBS) netting agreements, in order to assess whether this tool could successfully

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5 We use this expression to distinguish our topic from the much more explored issues of netting interbank off-balance-sheet exposures associated to OTC derivatives on the one hand (Bliss and Kaufman, 2006; Cont and Kokholm, 2014; Garratt and Zimmerman, 2017), and netting settlement agreements in payment systems on the other one (Angelini et al., 1996; Freixas and Parigi, 1998)).
complement the lending-of-last-resort measures a central bank customarily deploy to contain a systemic financial crisis (Cecchetti and Disyatat, 2010). An OBS netting deal is a bilateral arrangement that allows two parties to offset the mutual debt obligations they have registered on their books. By signing the new agreement, the two pre-existing gross claims are contractually replaced by the single net amount that the net-debtor owes to the net-creditor.

Under the regulatory framework outlined in the Basel Accords, such arrangements are permitted on a voluntary basis as privately stipulated contracts, while the rulebooks currently in place focus on the manner in which the net exposure resulting from a close-out netting effective upon a default has to be accounted for, how liquidity and capital requirements must be adjusted once the triggering event occurs, and under what conditions regulators are allowed to delay automatic close-out and termination rights to facilitate the orderly resolution of a distressed bank. While from a micro-prudential perspective it can be easily envisaged that OBS netting arrangements ends up to affect the seniority structure of debt, the implicit insurance against risks associated to borrowing and lending, and the drawing of internal limits for counterparty credit risk, their possible macro-prudential implications represent an almost uncharted territory.

In fact, the literature investigating the effect of OBS bilateral netting on the resilience of interbank lending networks is not only small, but it also returns discordant outcomes. Upper and Worms (2004) use data on the German interbank market to argue that the bilateral netting of mutual exposures could shrink the aggregate loss in asset values during an episode of crisis from 76% to 10%. Results for Belgium (Degryse and Nguyen, 2007) and the U.K. (Duan and Zhan, 2013) suggest a much weaker effect in reducing contagious defaults, however, while Eisinger et al. (2006) show that for Austria the consequence of introducing a bilateral netting arrangement is virtually irrelevant. As argued by Upper (2011), it is not clear whether this combination of mixed results have to be traced back to undetected differences in market microstructures, alternative hypotheses on the conditioning events, or the methodologies with which missing data on balance-sheet variables and unobserved linkages are obtained.

6 As will become clearer below, in our model the central bank counteracts a major liquidity turmoil through outright purchases of illiquid assets in the open market.
7 In a close-out netting agreement two parties agree that in the case of default of one of them, the obligations they have on each other are immediately terminated, the termination values are calculated and netted to arrive at a net single amount.
In order to explore the aptitude of interbank netting arrangements to tame systemic disruptions, we develop a financial network model suitably amended to make room for the possibility that mutual claims could indeed be netted on a bilateral basis. Building upon the “equilibrium cascade” algorithm for calculating total changes in liquidity proposed by Lee (2013), we use the model to study how funding shocks spread and get amplified through interbank linkages under alternative settlement arrangements. In our framework, liquidity shortages first arise when banks experience an unforeseen run on their deposits. This exogenous funding shock forces buffeted banks to recall their interbank assets and deploy their liquid reserves (if available) to meet their depositors’ demand for funds. A randomly chosen bank can hence be hit directly by a deposit shock or indirectly by the additional funding shock(s) imposed on it by other banks seeking to recover some additional liquidity in the interbank market. For this reason, ultimate liquidity needs might exceed the initial exogenous shock and bring about systemic liquidity shortages that could pose a threat to the whole system. Illiquidity driven disruptions are recorded whenever a bank faces liquidity needs in excess of its liquid assets (i.e. the sum of its interbank assets and liquid reserves set aside to comply with regulatory requirements).

We admit the possibility for a supervisory authority to regulate these operations by selecting the banks forced to activate OBS netting procedures. Five experimental treatments are explored. The first is a benchmark case in which netting is simply prohibited, so that contagion dynamics unravel in a network where all interbank exposures are gross. A full netting process characterizes the second case, where all banks are required to net their mutual claims regardless of whether they are experiencing a run on their deposits or not. We then test three hybrid treatments, in which a partial netting process is implemented so that netted and gross interbank claims coexist. In our third case, OBS netting is required only among the banks that do face a run on deposits. In the fourth case, the banks hit by an exogenous liquidity shock are forced to activate a netting settlement with safe counterparts only. Finally, in the fifth treatment a netting of mutual exposures is compulsory for non-affected banks only. These three latter policy options respond in varying degrees to alternative policy strategies aimed at limiting contagion, that is the attempt to isolate infected or susceptible nodes, respectively.

We evaluate how a mandatory enforcement of these netting protocols affect the performance of the interbank market under different scenarios on the size and distribution of exogenous liquidity shocks, as well as on the topological structure of interlinkages. As regards shocks, we first assume that only a small number of banks experience a hefty run on their deposits. We
then take the very same shock in aggregate terms and gradually spread it across a larger number of banks (each therefore suffering a smaller deposit withdrawal), ending with the case in which the run affects uniformly all banks. To accommodate the possibility that results could be driven by the topological architecture of interbank relationships, in addition to random Erdős–Rényi networks we perform simulations also for small-world and core-periphery structures. Finally, recognizing that the very notion of financial stability is multifaceted, the post-shock resilience of the system is evaluated along several – potentially conflicting – dimensions, namely the fraction of banks involved in the contagion, the ensuing systemic shortfall of liquidity, the distance to a potential condition of illiquidity of the banks that during the crises succeeded in preserving a positive liquidity position, and the volume of interbank transactions when the crises comes to a halt.

Our simulations make clear that the relative benefits and disadvantages of the netting regulatory option are firmly rooted on a typical “risk-sharing vs. risk-spreading” trade-off. On the one hand, it decreases the number of channels through which first- and higher-round infections spill over through the network. This implies that the potential for contagion can be reduced in proportion to the total value of mutual obligations that are offset. On the other hand, it contributes to concentrate losses not only on the banks hit by the original shock, but also on the ones whose original stock of unbalanced interbank positions disallow them to insulate. In other words, the benefit of reducing a spreading of contagion comes with an increase of the risk absorbed by the banks unable to fully disconnect themselves from the system.

We find that the balance between these two forces depends critically on the topological structure of the market. If the interbank market is characterized by a core-periphery architecture, substituting the standard gross settlement mode with a mandatory netting one does not provide on average significant advantages – although it does not do worse either – when the supervisory welfare criterion is defined in terms of the number of banks recording a liquidity strain, the total amount of liquidity shortage in the system, or the depth of the interbank market. The netting option works systematically better, however, when the policy target is that of assuring that the system comes out of the crisis in the best possible shape to face future negative shocks. Once characterized as a multiobjective problem on a suitably defined criterion space, therefore, a contingent-based mandatory netting scheme represents a Pareto optimal solution to pursue the multidimensional goal of financial stability. The actual magnitude of the Pareto improvement depends on the size and the distribution of the initial shock.
For random and small-world topological structures, however, the netting option represents an efficient crisis management tool as soon as the central bank targets the distance to illiquidity of survived banks or the post-contagion trading volume in the interbank market, but it performs significantly worse than the gross settlement mode whenever the policy goal is that of minimizing the shortfall of aggregate liquidity. In these cases, a policymaker faces a conundrum that can be resolved only if the several dimensions substantiating the broad concept of financial stability are organized hierarchically.

The remainder of the paper is as follows. Section 2 offers a brief introduction to OBS netting arrangements in light of the current regulatory environment, and discusses how they could be related to the issue of financial stability at large. Section 3 introduces the model. Section 4 illustrates results for the case of random interbank networks. Section 5 extends the analysis to alternative topologies. Section 6 concludes.

2 Netting as a systemic crisis management tool

The plausibility of the theoretical explanation for the existence of interbank markets based on mutual insurance resides in the empirical salience of bilateral deposit exchanges among banks. In the parlance of network theory, the scope for co-insurance can be measured by assessing how many nodes in a directed graph are linked to each other by reciprocal linkages. This measure — called reciprocity — can be calculated at least in two ways. First, by brute force as the ratio between the number of links pointing in both directions $L^{\leftrightarrow}$ and the total number of links $L$, so that $r = \frac{L^{\leftrightarrow}}{L}$ represents the average probability a link is reciprocated. In order to overcome problems of scale and double-counting of self-loops potentially affecting $r$, a second metric developed in the literature is the correlation coefficient $\rho = \frac{\sum_{i,j} (a_{ij} - \bar{a}) (a_{ji} - \bar{a})}{\sum_{i,j} (a_{ij} - \bar{a})^2}$ between the entries (given by $a_{ij} = 1$ if a link from $i$ to $j$ exists, and $a_{ij} = 0$ otherwise) of the associated adjacency matrix, where $\bar{a} = \frac{\sum_{i,j} a_{ij}}{n(n-1)}$ is the average density and $n$ is the total number of nodes in the network (Garlaschelli and Loffredo, 2004).

Regardless of the measure one employs, real interbank networks tend to display a substantial amount of reciprocity. Figure 1 reports the value of $r$ for the Euro-area e-MID market (Brandi et al., 2016), and of $\rho$ for a sample of large bilateral liability exposures among German banks (Roukny et al., 2014), in both cases measured at a quarterly frequency over the time span 2002:Q1-
2012:Q3. While the degree of reciprocity observed in these interbank markets has decreased in the aftermath of the 2007-09 global financial crisis, the scope for closing down possible channels of contagion through the bilateral netting of mutual exposures appears significant. The point is generally recognized by practitioners and trade associations, and both communities have long advocated for an extensive use of bilateral netting agreements as a means to mitigate counterparty risks and improve the liquidity of financial markets (British Banking Association, 2002; Mengle, 2010).

Figure 1. Values of $r$ for the Euro-area e-MID market (E-MID), and of $\rho$ for the German interbank market (DEU) over the period 2002:Q1-2012:Q3. Metrics defined in the main text. Sources: Brandi et al. (2016) and Roukny et al. (2014), respectively.

It is somehow surprising, therefore, that among the set of tools that regulators are envisaged to deploy to mitigate the cross-sectional dimension of systemic risk, the option to curb externalities by mandating some kind of netting between the cross-holdings of interbank deposits is virtually absent.\(^8\) Sections 401-407 of the United States’ Federal Deposit Insurance Corporation Improvement Act of 1991, for instance, admit and recognize the benefits of netting the payment obligations that financial institutions hold on behalf of their clients, but remain silent on the admissibility and usefulness of netting the deposits that banks exchange among themselves on the Fed Funds market. In turn, the legal framework of the European Union guarantees a legal protection only to privately-signed interbank bilateral close-out netting

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agreements (Directive 2002/47/EC, as amended by Directive 2009/49/EC), but for specific provisions that give regulators the power to delay their enforcement in order to guarantee the well-ordered resolution of a distressed bank (Banking Recovery and Resolution Directive 2014/59/EU).

While close-out netting agreements can be conceived as a tool to limit the first round of a contagion, we argue that a generalized enforcement of bilateral netting also among initially unaffected banks could help in mitigating higher-round effects, and therefore increase the resilience of the whole system. Specifically, this could be achieved by allowing a regulator to mandate the exercise of a novation netting agreement – according to which two parties cancel their mutual obligations out, and simultaneously replace them with a new obligation for the net amount – to a pre-defined set of interconnected banks as soon as the risk of a liquidity cascade materializes.

A major problem confronting regulators in the wake of a systemic financial crises is that of designing a coherent structure encompassing a multitude of agencies, instances and constraints. Defining the boundaries of the mandate to mitigate systemic risk they received is probably the most compelling task. Since financial stability is a highly multidimensional concept (Schinasi, 2004; Borio and Drehmann, 2009) and there is a potential for conflict between different dimensions, any operational framework supporting the prevention and management of financial crisis delivers in fact an array of working objectives. For instance, the Directive 2014/59/EU is explicit in recognizing that the set of tools available for recovering and resolving unsound or failing banks should aim to “[…] prevent insolvency or, when insolvency occurs, […] to preserve the systemically important functions of the institution concerned, […] while minimising the impact of an institution’s failure on the economy and financial system”.  

A crucial point to be addressed below is therefore that of defining a list of policy objectives a contingent-based mandatory netting scheme should aim for. Taking stock of the goals major central banks around the world declare to pursue in promoting financial stability (Jeanneau, 2014), we will assess the diverse netting options against four different dimensions of social welfare: i) To limit the number of units involved in the contagion; ii) If a contagion is unavoidable, to limit the strain of liquidity for the system as a whole; iii) To safeguard the financial health of safe banks; iv) To ensure that the interbank market does not come to a freeze.

9 Recall that close-outs come into force just upon a default triggering event, and can thus be exercised only by the counterparties directly exposed to the defaulted entity.
10 See Sections 1 and 5 of the BRR Directive.
The following steps consist in outlining a set of corresponding metrics – a task we shall leave to the next Section – and an evaluation of the trade-offs that the policymaker faces when different welfare objectives return contrasting results. Once defined in this way, in fact, the main goal of financial stability can be immediately translated into a multiobjective decision-making problem (Miettinen, 1999; Chankong and Haimes, 2008).

In formal terms, the problem can be expressed as follows. Let a high-level performance criterion be served through the minimization of the function:

\[ F^S(z) = \min\{f_1^s(z), f_2^s(z), \ldots, f_m^s(z) | z \in Z \}, \]  

where \( m \geq 2 \) is the number of possibly conflicting objective functions \( f(.) \), \( z \in Z \) defines the action space, and \( s \in S \) indexes the topology/microstructure scenario in which the optimization takes place. In our case, the high-level performance criterion is financial stability at large, the individual objective functions are the four dimensions of social welfare recalled above, while the set of policy actions comprises the alternative schemes for regulating mutual claims a regulator can choose from.

For any given structural scenario, an action \( z' \) Pareto dominates another action \( z'' \) if the two following conditions are met:

1. For all objectives, \( f_i(z') \leq f_i(z'') \forall i \in 1,2,\ldots,m. \)
2. For at least one objective, \( f_j(z') < f_j(z'') \exists j \in 1,2,\ldots,m. \)

This situation is particularly fortunate, as an optimal solution for the high-level performance criterion exists irrespective of the relative importance the policymaker attributes to individual objectives. If this occurs, a financial crises can be successfully managed by means of a single policy tool, ensuring that all the many facets of financial stability can be composed into a coherent picture.

If either of these conditions are violated, however, finding a Pareto-optimal solution requires to identify ways to prioritize conflicting objectives, so that the multiobjective problem is suitably transformed into a single-objective one admitting a Pareto frontier. Irrespective of the methodology actually employed – e.g., scalarization, goal programming, interactive approaches – the problem can now be solved only if detailed information on the preferences of the decision maker is available. Whenever the objective functions \( f(.) \) display nonlinearities, in turn, the corresponding single-objective program obtained by applying weights to individual objectives is not sub-additive, while the computational burden to generate solutions belonging to the Pareto frontier becomes extremely expensive.
The passage from the Directive 2014/59/EU reported above seems to suggest that regulators are well aware of the necessity to explicit their priorities when managing a crisis. Stipulating that their declared preferences are such that the general goal of a stable financial system can be pursued efficiently by means of the policy tools actually employed is a completely different matter, however. Approaching the issue of financial stability as a multiobjective decision-making process yields a fresh new perspective to the study of the optimal regulation of financial markets, a point that will be taken up repeatedly below.\textsuperscript{11}

3 The model
In this Section we describe how artificial financial networks with different topologies are built, the various settlement arrangements we study, the algorithm employed to calculate systemic liquidity shortages when contagion occurs, and the metrics used to assess the post-shock behavior of the interbank network. Our simulations advance according to a standard sequential procedure. At the beginning we characterize the network of interconnections among banks, as well as the assets and liabilities booked in their balance sheets. Then, we hit one or more banks by means of an exogenous shock to the liability side of the balance sheet. Finally, we apply different settlement treatments and comparatively assess the network’s performance along several dimensions.

3.1 Set-up of the network
The simplest way to computationally derive the network structure of an interbank system is to build a directed adjacency matrix using two main drivers: the number of links pointing out from each node, and the total number of banks. The first driver is captured by the probability $p_{ij}$ that a credit obligation between bank $i$ (depositor) and bank $j$ (debtor) - defined as $1_{ij}$ - happens, with $i \neq j$ and $i, j = 1, \ldots, N$. This operation returns, for each node $i$, the set of its borrowers $\Lambda_i$. If also $1_{ji}$ occurs, the possibility to net the two mutual expositions arises. The benchmark structure we consider is an Erdős–Rényi random network, where each node has a uniform attachment.

\textsuperscript{11} A similar view is advanced in Nier (2009), where the multidimensionality of financial regulation is referred to the coexistence of the two main goals of consumer protection and systemic risk mitigation. We claim that the even latter – i.e., financial stability writ large – is a multidimensional object in itself.
probability. In order to assess the role of market interconnectedness in propagating liquidity shocks, in what follows we will allow $p$ to vary. In turn, the size of the network is invariably given by $N = 25$.\(^{12}\)

Once the non-weighted network of relationships among banks has been shaped, the second step consists in assigning to each intermediary a stylized balance sheet consistent with a double-entry bookkeeping system (Table 1).

<table>
<thead>
<tr>
<th>Assets</th>
<th>Liabilities</th>
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<tr>
<td>$il_i$</td>
<td>$ib_i$</td>
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<tr>
<td>$q_i$</td>
<td>$d_i$</td>
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<tr>
<td>$z_i$</td>
<td>$e_i$</td>
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</tbody>
</table>

**Table 1.** Stylized balance sheet.

On the asset side, bank $i$ is endowed with an amount of illiquid external assets $z_i$, liquid assets $q_i$ and interbank lending $il_i$. On the liability side, in turn, each bank counts interbank borrowing $ib_i$, deposits $d_i$ and tangible equity $e_i$. By construction, the sum of the components on the asset side and of those on the liability side are equal ($il_i + q_i + z_i = ib_i + d_i + e_i$). We will assume that banks, when facing withdrawals, will recover funds by selling liquid external assets and interbank assets in constant proportion first. Only after all these assets are fully depleted, they can recur to illiquid external assets.

These latter can be liquidated at face value by selling them to the central bank, who consequently expands its balance sheet to accommodate the banking sector’s demand for extra liquidity by boosting the level of cash reserves. In the wake of the crisis, therefore, the central bank operates as a lender of last resort to avoid fire sales of assets and backing market functioning. The actual tool used to inject liquidity, that for simplicity in what follows we left unmodelled, is assumed to be an unsterilized outright asset purchasing program assimilable to the quantitative easing policy adopted by several central banks around the world in response to the 2007-09 global financial turmoil and the ensuing Euro-area sovereign debt crisis.

In order to populate the balance sheet of each bank, we start by exogenously fixing the amount of interbank assets $IA$ and we assign an equal portion of them to each bank, $il_i = IA/n$. We then obtain the amount of total assets as $TA = IA / (1 - \omega)$, where $0 < \omega < 1$, as well as the corresponding

\(^{12}\) This is the number used in the pioneering work of Nier et al. (2007). We refer to Gaffeo and Molinari (2015) for a discussion aimed at justifying this choice.
amount of external assets as $EA = TA - IA$. The value of each single loan that bank $i$ extends to a counterpart $j$ ($x_{ij}$) is finally achieved by dividing $il_i$ by the number of borrowers it is linked to. We can thus represent the interbank network by means of a weighted matrix $X$, where the horizontal summation returns $il_i = \sum_{j \in n_i} x_{i,j}$ and vertical summation $ib_i = \sum_{j \in n_j} x_{j,i}$. Note that interbank loans are slightly heterogeneous, given that the number of interbank debtors each bank has is potentially different. The stock of tangible equity of each bank is computed by multiplying the corresponding total assets by a parameter $0 < \gamma < 1$ measuring its leverage ratio. By difference we can then compute the amount of deposits, subtracting from the amount of total assets the value of each interbank borrowing plus the amount of equity. Finally, to obtain the level of liquid external assets ($q_i$) we multiply the volume of deposits by a parameter $0 < \delta < 1$, and we consequently decrease external assets to make sure that the double-entry bookkeeping holds. This guarantees that the network is fully identified and individual balance sheets are consistent with aggregates.

3.2 Alternative topologies
A quickly expanding empirical literature has pointed out that real interbank markets tend to display small-world and disassortative mixing structures in which low degree nodes form links with high degree nodes (Iori et al., 2008; Craig and von Peter, 2014; Fricke and Lux, 2015). As a robustness check we therefore extend our analysis to two topological architectures different from the purely random Erdős–Rényi case. Figure 2 illustrates comparable instances of the three structures we will deal with in simulations, from which the main features of the degree distribution characterizing each one of them can be appreciated.

The first alternative topology we consider is a clustered network exhibiting small-world properties, where the population of banks is grouped into five distinct clusters. All the nodes belonging to a cluster are fully connected to each other (intra-cluster probability of attachment $p_{cc} = 1$), but are also characterized by an inter-cluster probability of attachment $p_{ct}$ that we can vary from 0.20 to 1. All the other features of the financial system remains unaffected.

An additional disassortative structure is obtained by dividing the bank population into two samples, namely a core and a periphery. The banks in the core (hubs) are not only more connected, but also bigger than the peripheral ones. We model this architecture by choosing the number of hubs ($N_{large}$), so
that the number of banks in the periphery is obtained by difference \((N_{\text{small}} = N-N_{\text{large}})\). We then assign a probability \(p_s = 0\) to the links among peripheral banks, a probability \(p_l\) measuring how a hub connects to all kinds of banks, and a probability \(p_{sl}\) regulating the attachment between small and hub banks.

\[(a) \quad \quad (b) \quad \quad (c)\]

**Figure 2.** Different topologies for the lending (summation over rows) portion of the interbank market. (a): Erdős–Rényi network, with a common probability of attachment \(p = 0.2\); (b): Small-world network, with five fully connected clusters of five banks, and a common inter-cluster probability of attachment equal to \(p_{cc} = 0.2\); (c): Core-periphery network, with probabilities of attachment for core and periphery banks equal to \(p_l = 0.8\) and \(p_{sl} = 0.2\), respectively.

In order to allocate a balance sheet to each node we exogenously fix the benchmark size of three different types of interbank loans. The bigger one characterizes lending contracts among hubs, the medium size corresponds to the lending from peripheral to hub banks, and the smaller one represents the lending between hub and small banks. Given the interplay between attachment probabilities and loan sizes, the network is populated by highly interconnected big banks which can be net borrowers or lenders, depending on the value of the parameters, and small banks belonging to the periphery which are not interconnected among themselves. We divide the benchmark values of interbank loans by the number of links each bank has, in order to keep the size of total lending constant as the attachment probability characterizing hubs varies. Once the structure of interbank expositions has been shaped, we apply the same procedure described for the Erdős–Rényi case to fill in the remaining parts of individual balance sheets.

### 3.3 Contagion

We define the total liquidity of bank \(i\) as the sum of its interbank assets plus the total amount of its external liquid assets:
\[ l_i = \sum_{j \in N} x_{i,j} + q_i. \]  

(2)

Subsequently, we identify the proportion of interbank loans over the total amount of liquid assets as \( q_{ij} = x_{ij}/l_i \) for \( i, j \in N \), and the amount of external liquid assets over the total of liquid assets as \( q_{i,n+1} = q_i/l_i \) for \( i \in N \). This allows us to define the system in terms of a relative liquidity assets matrix \( \Phi \), and to use the latter in modelling contagion.

The algorithm we employ to calculate the complete sequence of knock-on effects arising from a liquidity shock is the one developed by Lee (2013). As shown in Hurd (2016), this is formally identical to the fictitious default algorithm developed by Eisenberg and Noe (2001) to derive the equilibrium clearing vector of payments over a contagion, the only differences being the nature of the shock that triggers a crisis and the direction of contagion. More precisely, while in the Eisenberg-Noe’s algorithm the propagation process begins with a loss on the asset side – so that it spreads from a debtor to a creditor bank - in the Lee’s algorithm the cascade begins with a deposit withdrawal on the liabilities side, and then it runs from a creditor to its debtors.

Operationally, the contagion process begins when an exogenous deposit run hits a given sample of intermediaries. In order to understand how the relative magnitude and distribution of shocks affect results, we will consider three different scenarios. In the first one, a randomly chosen small number of banks \( k \in N \) is disturbed by a major drawing of deposits, a situation we label “concentrated shock”. In the other two scenarios, we spread the same aggregate amount of deposits’ withdrawal over a larger sample of banks \( k' > k \) (“dispersed shock”) and over the whole population \( N \) (“generalized shock”), respectively. While keeping constant the absolute size of the shock allows an immediate comparison between the three cases, spreading it over different samples returns situations characterized by funding runs of different relative magnitude and distribution.

A bank affected by the shock needs to collect an adequate amount of liquidity to cover the unforeseen withdrawal of deposits using its liquid assets and, once liquid ammunitions have been exhausted, by selling illiquid assets to the central bank at face value. It follows that the shock, as it hits, can be defined as:

\[ \Delta d_i = \sum_{j \in N} \Delta x_{i,j} + \Delta q_i + \Delta z_i. \]  

(3)
Each affected bank responds by recalling an amount of interbank assets $\Delta x_{ij} = \phi_{ij} \cdot \min(\Delta d_i, l_i)$, an amount of liquid external assets $\Delta q_i = \phi_{in+1} \cdot \min(\Delta d_i, l_i)$, and one of illiquid external assets $\Delta z_i = \max(0, \Delta d_i - l_i)$. The total change in liquid assets for a given bank $i$ can exceed the exogenous shock $\Delta d_i$, while the exact value of such change can be efficiently computed by solving the system of equations:

$$\Delta l_i = \min[l_i, \sum_{j \in N} q_{ij} \cdot \Delta l_j + \Delta l_i], \forall i \in N.$$  \hspace{1cm} (4)

A soon as the mapping describing the liquidity knock-on mechanism converges, the Knaster-Tarski Fixed Point theorem guarantees that at least one exact solution to (4) exists and can be calculated in a finite number of iterations. This is verified if the mapping is monotone nondecreasing in the outflow of liquidity experienced by banks, a condition that holds true due to the seniority structure we have assumed before. If the relative liquid exposure matrix $\Phi$ is irreducible substochastic, furthermore, the equilibrium clearing vector of funding withdrawals is unique.

The liquidity need of bank $i$ is thus given by:

$$l_i^* = \sum_{j \in N} q_{ij} \cdot \Delta l_j + \Delta l_i,$$  \hspace{1cm} (5)

corresponding to the sum of the deposit withdrawal it originally faces from its depositors and the request of liquidity by the set of its creditors needing liquidity. Every time $l_i^* > l_i$, a bank experiences a liquidity shortage computed as $\lambda_i^* = l_i^* - l_i$. If $l_i^* > 0$, the bank is forced to enter into the outright asset purchase program deployed by the central bank. We define a systemic liquidity shortage (SLS) as the sum of the liquidity shortages suffered by all the banks belonging to the network.

### 3.4 Settlement procedures

The potential of a mandatory OBS netting scheme as a crisis management policy is assessed by comparing the performance of five settlement treatments. The first one is the standard gross settlement (G) mode, which represents our benchmark. In this case we left unchanged the weighted matrix of interbank loans $X$ obtained through the two initiation stages discussed above. The second treatment is a full netting (FN) scenario, where each bank is allowed to offset his bilateral credit/debit obligations. The
matrix $X$ is consequently rearranged by applying an algorithm that computes the net mutual exposition between any two banks $(x_{i,j} - x_{j,i})$. To exemplify, if the original 2x2 matrix $X$ is:

$$X = \begin{bmatrix} 0 & 2 \\ 1 & 0 \end{bmatrix}$$

when the regulator forces an OBS netting it becomes:

$$X' = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}.$$

Then we test three intermediate cases of partial netting. In the first case ($P$-I) we assume that the bilateral netting of mutual exposures is mandatory only for the banks that receive the external shock. In the others two cases the netting treatment is applied between distressed and non-distressed banks ($P$-II), and among non-distressed banks only ($P$-III), respectively. For example, consider the network be composed of four banks interlinked by mutual exposures as in the matrix $X$ below. Suppose that the first two intermediaries are hit by a run. The weighted matrix $X$ now becomes $X'$, $X''$ and $X'''$ for the three partial netting schemes just recalled, respectively.

$$X = \begin{bmatrix} 0 & 1 & 0 & 2 \\ 2 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 2 & 2 & 2 & 0 \end{bmatrix}; \quad X' = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 2 & 2 & 2 & 0 \end{bmatrix}; \quad X'' = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 2 & 2 & 0 & 1 \\ 2 & 2 & 0 & 0 \end{bmatrix}; \quad X''' = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 2 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix}.$$  

This example also makes clear that any kind of netting reinforces the strict substochasticity of the associated relative exposures matrix $\Phi$, that represents a necessary and sufficient condition for the uniqueness of the payments clearing vector solving the fixed point problem (4). In other words, if the network $X$ is such that a clearing vector exists and is unique, the same holds true for $X'$, $X''$ and $X'''$ as well.

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$^{13}$ See Theorem 2.2 in Hurd (2016, pp.25-27).
3.5 Metrics for policy objectives

The settlement options described above are assessed comparatively against four metrics measuring different dimensions of financial stability. The first is the troubled banks rate, defined as the fraction of banks forced to resort to the assistance of the central bank to sell their illiquid assets as the contagion proceeds. Operationally, we define a binary variable \( t_{bi} \), for \( i \in N \), which takes the value 1 if the \( i^{th} \) bank goes short of liquidity at some point, and 0 if the bank withstands the contagion process without the need to liquidate any of the illiquid assets it has on its books. The troubled banks rate can thus be computed as \( \sum_{i \in N} t_{bi} / N \).

The second metric measures the dearth of systemic liquidity, obtained by adding up the individual liquidity shortages \( l_i \) relative to the size of individual external illiquid assets \( z_i \), i.e. \( \sum_{i \in N} l_i / \sum_{i \in N} z_i \). Complementary to the previous metric, which focuses on the extensive margin, this one allows us to measure the intensive margin of the liquidity shortfall experienced by the whole market. By combining the two indicators, one can gain information on the latitude and magnitude of the exceptional liquidity injection the central bank is bound to extend in managing the liquidity crisis. As a result, our analysis permits to appreciate how alternative options on the way interbank exchanges are settled might interact with standard lender-of-last-resort functions deployed by monetary authorities.

The third index measures the percentage erosion of liquid means faced by the banks withstanding contagion without having to prematurely liquidate illiquid assets. As such, it can be read as an average distance to illiquidity in the case a new shock occurs, which we take as a proxy for the health of the banking system in its post-contagion state. The distance to illiquidity for viable banks is therefore computed as the ratio between the total amount of liquid external assets employed to confront the unexpected withdrawal of external or interbank deposits and the total amount of initially available liquid assets, where summations are taken over the set of banks that during the crisis episode never resorted to the lender-of-last-resort facility made available by the central bank. The domain of this variable is by construction defined in the interval \([0, 1]\). The upper bound is reached when almost all the liquidity of untroubled banks is employed during the contagion process. On the contrary, the metrics tends to zero when their aggregate stock of liquidity has been preserved despite the crisis.

The final metric deals with the post-contagion depth of the market expressed in terms of the volume of interbank deposits. It is computed as the difference between the total interbank assets before the shock occurs \( \sum_{i \in N} A_i \) and the total interbank assets after the shock occurs \( \sum_{i \in N} A_i - \sum_{i \in N} l_i \).
and the interbank assets employed during the contagion or in the netting process $\sum_{i\in N} EIA_i$ all divided by $\sum_{i\in N} IA_i$. Higher values of this index signal that the scope for co-insurance in managing idiosyncratic liquidity needs under post-crisis normal conditions has not been impaired during the turmoil generated by the funding run.

3.6 Overview
The framework we offer to weigh in the pros and cons of forcing the netting of interbank bilateral exposures when a liquidity crisis occurs is rather complex. It seems worthwhile to summarize in Table 2 the various instances we consider for: i) the two key variables driving the dynamics of contagion, i.e. the topological structure of the market and the type of shock hitting the system; ii) the crisis management option chosen by the regulator; iii) the goal used to evaluate the social welfare of any given policy prescription.

<table>
<thead>
<tr>
<th>Topological scenarios</th>
<th>Distribution of shocks</th>
<th>Settlement Treatments</th>
<th>Welfare criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erdős–Rényi</td>
<td>Concentrated</td>
<td>Gross</td>
<td>Troubled banks rate</td>
</tr>
<tr>
<td>Small-world</td>
<td>Dispersed</td>
<td>Full netting</td>
<td>Liquidity shortfall</td>
</tr>
<tr>
<td>Core-periphery</td>
<td>Generalized</td>
<td>Partial netting I</td>
<td>Distance to illiquidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial netting II</td>
<td>Depth of the market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Partial netting III</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Overview of the simulation framework.

In what follows, all graphs will report profiles corresponding to the value registered by each welfare criteria at the end of the contagion process – calculated as the fixed point of the cascade mapping generated by the fictitious default algorithm (4) – for different levels of interconnectedness.

4 Random networks
We start our analysis from the Erdős–Rényi topology. Table 3 summarizes the baseline simulation parameters. Since our scope is purely explorative, none formal external validation has been performed. Nevertheless, calibration values are fully consistent with the ones customarily used in the literature we are building upon (Niet et al., 2007; Gai and Kapadia, 2010; Lee, 2013).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Baseline calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Number of banks</td>
<td>25</td>
</tr>
<tr>
<td>$\omega$</td>
<td>External assets ratio</td>
<td>0.83</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Leverage ratio</td>
<td>0.04</td>
</tr>
<tr>
<td>$\delta$</td>
<td>External liquid assets ratio</td>
<td>0.03</td>
</tr>
<tr>
<td>$p$</td>
<td>Interconnectedness probability</td>
<td>(0.2, 1)</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Size of the funding shock as a % of deposits</td>
<td>25% - 8% - 4%</td>
</tr>
<tr>
<td>$k$</td>
<td>Number of shocked banks</td>
<td>4 - 12 - 25</td>
</tr>
</tbody>
</table>

Table 3. Parameters and calibration for the Erdős–Rényi topology.

Figure 3 reports results for a concentrated shock scenario, in which the depositors of four randomly chosen banks suddenly withdraw 25% of their deposits. The upper-left panel of the figure shows that the five types of interbank settlement perform in a fully comparable fashion as far as the troubled banks rate is concerned. Systemic liquidity shortages are slightly stronger under the $FN$ and the $P$-II treatments (upper-right panel), however, especially at the high end of the connectivity spectrum. The situation is completely reversed along the distance to illiquidity dimension (lower-left panel), where both $FN$ and $P$-II engender a considerable advantage with respect to the $P$-I, $P$-III and $G$ cases, respectively.

These findings are the consequence of two distinct effects. The first one implies a typical balancing between a risk-sharing and a risk-spreading effect.
On the one hand, OBS netting schemes cut several potential channels of contagion by isolating the banks with interbank positions that can be netted almost in full. On the other hand, any netting settlement operates to disconnect the interbank market, lowering the risk-sharing associated with a mutual exchange of interbank deposits. In particular, the decreased scope for sharing liquidity risks comes with a stronger concentration of liquidity calls to those debtors who cannot fully net their position towards distressed banks. From this point of view, netting settlements contribute to increase financial instability. Moreover, there is a second effect weighing the liquidity shortage registered at the aggregate level against the distance to illiquidity of untroubled banks, that depends on the relative magnitude of the external run disturbing intermediaries. For a funding shock large enough, the netting of mutual claims increases the internalized portion of the unexpected depositors’ withdrawal. As a result, it tends to increase the liquidity shortfall of shocked banks on the one hand, while lowering the liquidity calls towards the remaining part of the network on the other one. This is the reason why the distance to illiquidity tend to be structurally lower in the netting treatments including shocked banks. In fact, the internalization of a larger portion of knock-on losses implies a lower liquidity need during the whole contagion process. Whilst the two effects tend to offset each other in terms of the fraction of banks incurring into liquidity troubles, this is not the case for the other welfare metrics. In the FN and P-II treatments, the concentration effect increases systemic liquidity shortages if compared to the standard G treatment, as well as to the P-I and P-II ones. Symmetrically, the losses’ aggregation process allows FN and P-I to outperform all other treatments as far as the index of financial health after contagion is concerned.

The lower-right panel of Figure 3 illustrates the post-crisis depth of the interbank market under the five settlement protocols. In the four treatments considering the netting of mutual exposures, results are driven by two ingredients. The first is the internal dynamics associated to novation wiping out interbank contracts, while the second one is the contagion process forcing intermediaries to call back interbank credits. For the G treatment, on the contrary, the only reason for the shrinkage of the interbank market is due to the standard dynamics of the liquidity cascade.

Figure 4 reports simulation results for the case of a more dispersed shock, with 12 banks experiencing a 8% decrease of their deposits. It appears that the defensive P-II treatment represents the best possible option whenever the policy objective consists in maximizing the post-crisis deepness of the interbank market, while it guarantees an almost optimal solution for all the other cases in cohabitation with the FN treatment. It follows that although the
netting of interbank deposit contracts acts to shrink the interbank market in general, a policy prescription targeted at isolating safe nodes as the one devised by the partial netting II treatment consistently preserve the cut-out part of the network from contagious spirals.

![Figure 4](image)

**Figure 4.** Performance profiles over the interconnectedness spectrum for the different crisis management options, when the topology of the interbank market is Erdős-Rényi. The case analysed is for 12 distressed banks due to a 8% deposit withdrawal each.

Lastly, we consider an outflow equal to 4% of the deposits at each bank populating the network. By construction, the three partial netting schemes now collapse to the FN case. As shown in Figure 5, netting works better than the standard gross settlement in preserving the healthier part of network (lower-left panel), while showing a comparable performance along all the other metrics.

This analysis suggests that in Erdős-Rényi financial networks a crisis management plan aimed at forcing the netting of mutual interbank deposits might represent a viable and efficient option to control systemic financial disruptions, as soon as the many operational targets substantiating the multidimensional concept of financial stability are suitably defined and prioritized. While in general mandatory netting protocols does not significantly alter the defaults’ profile typically associated with the gross settlement of interbank debts, a regulator requiring that a bank distressed by a deposit run nets its interbank exposures against unaffected counterparties would do a good job in preserving the volume of transactions in the interbank market and the financial health of the banks surviving the crisis.
A state-contingent binding scheme to net mutual interbank obligations heightens the shortage of liquidity suffered by the whole system, however. This is due to the trade-off between the better protection against contagion for those who net and the higher concentration of losses on those who remain part of the network. As shown above, the extent of conflict among the different dimensions of financial stability is magnified when the deposit run igniting the crisis is stronger and more concentrated.

This makes the multiobjective problem faced by policymakers particularly tough. Policy action requires not only that authorities have access to real-time data on the exact liquidity position at each bank (indeed a standard circumstance under current regulatory practices), but also that they deploy and made public a vision of how the different stances of financial stability contribute in composing a coherent and transparent crisis management framework. For instance, if the macroprudential policy model is inspired to a two-pillar architecture (Schoenmaker and Wiert, 2011), so that the roles and responsibilities of the lender-of-last-resort are formally separated from those of the agency in charge of regulating financial markets and institutions, it should be explicitly acknowledged from the start that any attempt to maximize the possibilities of recovery from a systemic liquidity crisis by intervening on the interbank settlement microstructure has to be buttressed by a stronger expansion of the central bank’s balance sheet. The marginal cost
of unwinding it when normal market conditions will prevail should therefore be taken into account.

As we will see in the next Section, the relevant information set needed to assess all the facets of this conundrum has to be moreover complemented by an accurate knowledge of the topological structure characterizing the interbank market.

5 Disassortative networks
The random architecture analysed so far represents a natural benchmark to consider. As already recalled, however, real-world interbank networks have been shown to possess strongly disassortative mixing degree distributions, with a few banks having substantially more connections than the average degree. Since the key idea at the root of a crisis management strategy based on a mandatory OBS netting is that of cutting links to contain contagion, it seems interesting to explore how its implementation could perform in topologies alternative to the random one.

5.1 Small-world networks
The first robustness check we fulfil refers to a small-world topology, in which banks are organized in tightly connected clusters, while each cluster is slightly connected to all the others through short paths. Table 4 summarizes the baseline simulation parameters characterizing this experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Baseline calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_c$</td>
<td>Number of clusters</td>
<td>5</td>
</tr>
<tr>
<td>$p_{ic}$</td>
<td>Intra-cluster interconnectedness probability</td>
<td>1</td>
</tr>
<tr>
<td>$p_{cc}$</td>
<td>Inter-cluster interconnectedness probability</td>
<td>(0.2, 1)</td>
</tr>
<tr>
<td>$\Delta d$</td>
<td>Size of the funding shock as a % of deposits</td>
<td>20% - 10% - 4%</td>
</tr>
<tr>
<td>$k$</td>
<td>Number of shocked banks</td>
<td>5 - 10 - 25</td>
</tr>
</tbody>
</table>

Table 4. Parameters and calibration for the small-world topology. Parameters not reported are equal to the ones employed in the Erdős–Rényi case.

Figure 6 reports results for a concentrated shock scenario, in which the depositors of all the five banks belonging to a randomly chosen cluster suddenly withdraw 20\% of their deposits. As usual, we apply the four netting treatments and the benchmark gross settlement mode in a comparative fashion. The first noteworthy feature is that, in line to what we observe for random networks, the different profiles over the whole interconnectedness range for the fraction of troubled banks are essentially undistinguishable,
signalling that the contagion-preserving and the loss-concentration effects tend to offset each other. The balance between the two prongs of the trade-off drives both the bad performance of the FN and the P-II treatments as regards the metric measuring liquidity shortages, as well as their good score in the distance to illiquidity metric. Due to their relative inability to isolate the shock affecting the stressed cluster, in turn, P-I and P-III turn out to be systematically less effective than the other netting treatments. Moreover P-III, due to the large number of netted contracts it allows, lowers the depth of the interbank market without being able to score an improvement along the other welfare dimensions. All in all, P-II is as effective as FN along the distance to illiquidity dimension, and it is also the best treatment in preserving the deepness of the interbank market.

Figure 6. Performance profiles over the interconnectedness spectrum for the different crisis management options, when the topology of the interbank market is small-world. The case analysed is for a cluster of 5 distressed banks due to a 20% deposit withdrawal each.

The following scenario is one in which the liquidity shock triggering contagion is preserved in aggregate terms but more dispersedly distributed. In particular, we assume that the banks belonging to two distinct clusters experience a withdrawal of 10% of their deposits. As shown in Figure 7, the findings we obtain are similar to the ones we get with the previous set of simulations. The metric measuring the extensive margin of the quantitative easing shows an identical profile for all the treatments. The loss-concentration effect tends to preserve the financial health of safe banks by putting the whole burden of the shock on the intermediaries facing liquidity problems. For this
reason, $P$-II and $FN$ register the best performance on the distance to illiquidity metric, while the situation is completely reversed along the liquidity shortage dimension. In the latter case, treatments $G$, $P$-I and $P$-III represent an optimal solution. Finally, $FN$ underperforms all the other treatments in preserving the depth of the interbank market, while $P$-II shows the best performance also for this metric. As in the previous scenario, the $P$-II treatment dominates as regard at least two metrics, even if it is not a Pareto optimal solution.

Figure 7. Performance profiles over the interconnectedness spectrum for the different crisis management options, when the topology of the interbank market is small-world. The case analysed is for a cluster of 10 distressed banks due to a 10% deposit withdrawal each.

In the third small-world scenario we hit all the banks of the network by means of a generalized bank run amounting to 4% of individual deposits. Since all banks are shocked, the $G$ and the $FN$ treatments are the only available options. Figure 8 reports our findings. The two settlement modes show similar dynamics except for the distance to illiquidity metric, where the loss-concentration effect characterizing netting prevails. This occurs because a larger portion of the original deposit withdrawals is immediately internalized by shocked banks, with the consequence that a lower amount of liquidity calls is spread out over the system. If forced to net their interbank claims, shocked banks experience stronger liquidity shortages. As the liquidity contagion proceeds, however, a lower portion of the shock is effectively passed through at each stage, so that the initial higher systemic liquidity shortage associated to $FN$ converges to the one generated by the $G$ treatment.
in correspondence of the equilibrium payment vector. In view of that, the FN treatment represents a Pareto dominant solution to the multiobjective problem of financial stability whenever a generalized shock affects a banking network arranged according to a small-world architecture.

5.2 Core-periphery networks
As a last experiment, we test our model on a core-periphery topology. Table 5 summarizes the baseline simulation parameters. Three types of shocks – assumed to possess the same initial aggregate magnitude – are considered, respectively to one core bank, to four core banks and to seventeen small banks. We first shock one core bank by means of a 100% withdrawal of its

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Baseline calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{hubs})</td>
<td>Number of hubs</td>
<td>4</td>
</tr>
<tr>
<td>(p_{st})</td>
<td>Small-to-hub interconnectedness probability</td>
<td>0.4</td>
</tr>
<tr>
<td>(p_{hi})</td>
<td>Hub interconnectedness probability</td>
<td>(0.4, 1)</td>
</tr>
<tr>
<td>(l_p)</td>
<td>Small-hub, hub-small and hub-hub loan size</td>
<td>1 – 3 - 5</td>
</tr>
<tr>
<td>(\Delta d)</td>
<td>Size of the funding shock as a % of deposits</td>
<td>100% - 25% - 4%</td>
</tr>
<tr>
<td>(k)</td>
<td>Number of shocked banks</td>
<td>1 - 4 - 17</td>
</tr>
</tbody>
</table>

Table 5. Parameters and calibration for the core-periphery topology. Parameters not reported are equal to the ones employed in the Erdős-Rényi case.
deposits. By construction, the analysis is limited to the gross and full netting treatments only.

As one can see in Figure 9, both treatments yield the same dynamics in terms of the troubled banks rate and liquidity shortages, suggesting that the contagion-preserving and loss-concentration effects tend to offset each other. Netting clearly dominates gross settlement when they are evaluated against the dimension capturing the distance to illiquidity, while the opposite holds true when one focuses on the depth of the interbank market. In this case, the loss-concentration effect forces the buffeted bank to internalize a higher portion of the shock whenever regulators force it to net. For such a reason, the remaining call-back of interbank deposits wipes out a lower amount of liquid resources from safe banks. In turn, once the contagion process comes to a halt the netting procedure engenders a shallower interbank market. Once again, none treatment turns out to be Pareto dominant.

Figure 9. Performance profiles over the interconnectedness spectrum for the different crisis management options, when the topology of the interbank market is core-periphery. The case analysed is for a hub bank affected by a 100% deposit withdrawal.

Next, we simultaneously shock the four banks at the core of the system, with a run as large as 25% of their deposits. In this case, all the partial netting treatments previously described can also be tested. As shown in Figure 10, FN and P-II outperform the other treatments in preserving financial stability after contagion. The other three metrics remained approximately equal, a finding that can be explained as follows. Since safe banks – i.e., those not hit by the exogenous shock – belong to the periphery and are not connected to each
other, P-III collapsed to G. Moreover, P-I generates a contagion dynamic similar to those of G. Although shocked banks are forced to net their mutual exposures, the very fact that all the hubs are hit by the same shock left their liquidity needs unchanged. FN and P-II score a better performance with respect to the distance to illiquidity, due to the fact that the loss-concentration effect associated to netting acts to limit the volume of liquidity drained from the system by shocked banks.

Finally, we test a situation in which all the seventeen small banks belonging to the periphery are shocked. In order to keep the size of the shock comparable to the two former cases, we model a bank run of 40% of their deposits. As we can see in Figure 11, FN and P-III outperform the other treatments along the distance to illiquidity metric and perform in a comparable fashion in all the other dimensions. For the FN case, the lower distance to illiquidity is mainly due to the loss-concentration effect distressing shocked banks, while on the other three metrics the contagion-prevention and the loss-concentration effects offset each other. The reason for the good performance of the P-III treatment as regard the financial health of viable banks can be derived as follows. When core banks receive liquidity calls from shocked peripheral banks, they immediately call back their interbank loans towards the shocked periphery, forcing an arrest to the propagation of liquidity contagion. On the contrary, when core banks are connected to each
other, they call back their interbank assets by asking other hub banks first. This implies an initial higher depletion of liquidity, although the final systemic liquidity shortage remain unaltered.

![Figure 11](image.png)

**Figure 11.** Performance profiles over the interconnectedness spectrum for the different crisis management options, when the topology of the interbank market is core-periphery. The case analysed is for 17 periphery banks facing a 40% deposit withdrawal each.

Summarizing, when the banking network is characterized by a core-periphery topology we find a strong advantage for the full netting treatment. This results to be a Pareto dominant solution for both disperse and almost generalized shocks.

### 6 Concluding remarks

The key objective of this paper was to shed light on the effects exerted by a contingent-based OBS netting prescription on the mitigation of systemic financial disruptions. In particular, we have employed numerical simulations to investigate whether a deposit run could trigger a systemic liquidity crisis more easily in an environment in which a standard gross settlement mode is applied in settling interbank lending exposures, in comparison to an environment in which alternative OBS netting schemes are used as a crisis management tool. The impact of OBS netting has been assessed against several metrics capturing the multidimensionality of financial stability, such as the fraction of banks asking for a liquidity support to the central bank, systemic liquidity shortages, the distance to illiquidity for the banks that
never went short of liquid means during the whole crisis, and depth of the interbank market after contagion.

Our simulations highlight that the scope for forcing banks to net their mutual claims in an attempt to defuse possible channels of contagion implies that regulators face a crucial trade-off, whose balance varies depending on the inner dynamics of clearing arrangements. A bilateral netting settlement mode tends to concentrate interbank liquidity calls towards a lower number of counterparties. This effect weakens the potential to share liquidity risks associated to mutual interbank loans, worsening the prospect to be exposed to a financial pain for all the banks who are not allowed to fully disconnect themselves. In turn, given that novation agreements reduce the interbank depth, a netting of bilateral exposures contributes to cut several channels of contagion. The interplay between these two forces determines the final outcome.

For Erdős–Rényi and small-world topologies we identify an advantage of the FN and P-I treatments in preserving the financial health of the banks who went through the crisis with a positive liquidity position. At the same time, however, the concentration effect operates to magnify liquidity outflows for infected banks. For this reason, the two netting treatments underperform the gross settlement one as far as systemic liquidity shortages are concerned. The interplay between the concentration and the risk-sharing effects tends to homogenize the share of banks struggling for liquidity at a common value for all the treatments under scrutiny. Although a Pareto-dominant treatment does not clearly arise, the P-I settlement mode performs better than all the others along two out of four dimensions of financial stability. Indeed, this treatment is particularly indicated if the regulator expects a multiple-shock dynamics, given that is guarantees a higher level of resilience for survivor banks and a more deep interbank market.

As we proceed to core-periphery structures, a clear policy prescription emerges for disperse and generalized shocks, situations in which the FN treatment outperforms the other crisis management options along the distance to illiquidity metric, whilst performing comparatively well in all the other cases. All partial netting treatments operate to isolate core banks from the rest of the system, avoiding the spread of contagion. For the case of a funding shock targeted at a single core bank a Pareto dominant solution does not exist. FN remains the best option as far as the distance to illiquidity metric is concerned, while it performs in line with the gross settlement mode when the rate of troubled banks and liquidity shortages are taken into account. Still, a gross settlement of interbank exposures preserve in a more efficient way the volume of transactions, leaving to the regulator the tough judgment on how
to prioritize between the distance to illiquidity and the depth of the interbank market when choosing its welfare target.

By allowing banks to participate in an outright asset purchase program orchestrated by the central bank, the present model neglects completely market illiquidity. This assumption was retained in order to keep liquidity runs detached from the dynamics generated by failure cascades affecting the assets’ side. Future improvements should relax this hypothesis. Our intuition is that in this case another important trade-off would enter the scene as soon as an OBS netting scheme was made mandatory to face a systemic liquidity shortfall, in that the higher fire selling losses generated in a more interconnected market should be weighed against the relative financial position of those banks that (partially) succeed in insulating themselves from contagion at the cost of bearing more concentrated liquidity shortages.

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