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The impact of network inhomogeneities on contagion and system stability

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The impact of network inhomogeneities on contagion and system stability

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Abstract

This work extends the contagion model introduced by Nier et al. (2007) to inhomogeneous networks. We preserve the convenient description of a financial system by a sparsely parameterized random graph but add several relevant inhomogeneities, namely well-connected banks, financial institutions with disproportionately large interbank assets, and big banks focusing on wholesale and retail customers. These extensions significantly enhance the model's generality as they reflect inhomogeneities as found in reality with a potentially decisive impact on system stability. Whereas well-connected banks and big retail banks have only a surprisingly modest impact, we find a significantly enhanced contagion risk in networks containing institutions with disproportionately large interbank assets. Moreover, we show that these effects can be partly compensated by a suitable regulatory response which demands additional net worth buffers for banks with above average volume of interbank assets. The stabilising effect is most notably achieved by a pure redistribution of equity capital without increasing its total amount.

Keywords: capital buffers, contagion, contagious defaults, inhomogeneities, network models, financial system stability

JEL Classification: C63, G21, G28

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I Introduction

The recent financial crisis has strikingly revealed the global nature of financial connections: An apparently local problem with American sub-prime mortgages evolved into a truly global financial crisis. It is, therefore, no surprise that systemic risk, which is key for the understanding of financial crises, has become a widespread subject of public discussion and scientific research. Shock transmission between the banks of a financial system is a crucial mechanism behind systemic risk. Accordingly, systemic risk has even been defined as the possibility "that cumulative losses will accrue from an event that sets in motion a series of successive losses along a chain of institutions or markets comprising a system. [...] That is, systemic risk is the risk of a chain reaction of falling interconnected domino" (Kaufman and Scott, 2003).

This paper generalizes the network model introduced by Nier et al. (2007) to the more realistic situation of inhomogeneous networks. We preserve the clear and convenient basic scheme to construct banking networks based on random graphs where the structure of the financial system is characterised by very few key parameters. The model's basic evaluation parameters are the general net worth level (i.e. the leverage of every bank), the probability that two banks in the system are connected (connectivity), and the size of interbank exposures in the system (fraction of the interbank market). Systematic variations of these parameters allow the study of relevance and impact of these network characteristics on its stability. Even in the model's simple and highly stylized structure, revealing influences have been found. These include a non-linear dependence of contagion risk on leverage and a non-monotonic (M-shaped) dependence on the connection probability.[1] However, due to the model's strict homogeneous structure, which is unrealistic given the big differences between banks in reality, the results lack generality. In order to study the impact of inhomogeneities on the stability of financial networks we propose three extensions to the homogeneous model, namely well-connected banks, financial institutions with disproportionately large interbank assets, and big banks focusing on wholesale and retail customers.

Network models have proven very helpful for the study of shock propagation and a system's resilience to contagion (Allen and Babus, 2009). They are also a tool to investigate the effects of regulatory requirements. Network models represent a financial system and its interdependencies as a collection of nodes and links between those nodes, i.e. as a mathematical "graph". The nodes describe the agents, e.g. the banks in the system, where each bank is given as a stylized balance sheet. The edges represent contagion channels which may propagate a shock, typically a default, from one bank to a neighbouring one. The most basic such channel consists of directional lendig relationships which are described by the matrix of exposures (Upper, 2007).

[1] This relation has been confirmed in several subsequent papers (e.g. Gai and Kapadia, 2010; Čihák et al., 2011)

Further contagion channels, like impacts on asset prices or interlinkages via derivatives, may also be included (Gai and Kapadia, 2010). On this abstract level, findings from areas "as diverse as collective action, the diffusion of norms and innovations, cultural fads, and cascading failures in infrastructure and organizational networks" (Čihák et al., 2011) become applicable to financial systems. Simulations allow to investigate how contagion spreads and what causes a system's fragility. For this purpose, a well-defined shock, e.g. the default of a particular institution caused by losses in its assets, is propagated through the network in order to identify the contagious defaults. Similarly, systemic shocks can be simulated, where all banks suffer sudden losses at the same time.

The three extensions which we introduce to the network model by Nier et al. (2007) reflect realistic inhomogeneities as found in real world financial systems and are suspected to influence system stability to a significant extent. First, we are interested in the role of well-connected banks which are characterized by a high node degree. Such banks are implemented in the model by replacing the fixed probability for a link with a suitable probability distribution to generate pair-dependent connection probabilities. Second, we consider banks with a strong position in the interbank market. A bank with high net interbank lending or borrowing is considered risky. An individual node property "riskiness" is introduced by a non-homogeneous distribution of the link weights. Third, we propose a non-homogeneous distribution of the external assets which reflects different business models. A bank with high external assets focuses on retail or business loans while a bank with low external assets primarily is active in the interbank market (wholesale). Significant distinctions are again introduced into the model by assigning the amount of external assets to individual banks according to an unequal probability distribution. Our implementation of inhomogoneities strictly preserves the parameter-based characterization of the networks. Each type is goverened by an additional new parameter which shapes the according probability distribution. This allows to study different degrees of inhomogeneity and their interactions in a very differentiated and controlled way.

Having included the three inhomogeneous elements, we run similar simulations as done in Nier et al. (2007). However, due to a very efficient model implementation, much lager networks are studied. While Nier et al. (2007) only consider networks with 25 banks we perform our simulations for up to 250. In this way we are able to check finite size effects, which turn out to be rather moderate as long as a comparable number of network links per node is used. A shock is modeled as the default of an arbitrary bank. This causes losses at creditor banks which may trigger further defaults. Similar to Nier et al. (2007), we study the default dynamics with respect to the three basic network characteristics bank capitalization (net worth level), connectivity, and interbank exposure. When reporting results, we concentrate on the worst case scenario as this best describes the fragility of the system, but average figures have been evaluated as well.

Our main finding is that the type of inhomogeneity is crucial. While different distributions of the connectivity and the external assets only moderately change the results, an unequal distribution of net interbank exposures significantly increases contagion risk. This holds true with respect to variations of all three network characteristics. With inhomogeneous net interbank exposures the shapes of the dependence functions change completely. In particular, the well known M-shaped dependence with respect to connectivity is wiped out. Interestingly, these effects only show up in full in the worst case scenarios but not for the average figures. This indicates that banks with disproportionately large net interbank positions significantly increase the contagion risks in the financial network. The existence of just well-connected banks as modelled by a connectivity distribution, in contrast, only moderately enhances risk. Different business models (distribution of external assets) do not increase contagion risk in general but alter the default dynamics as evidenced by the different shapes of the dependence functions.

In a second step, we use the inhomogeneous model to explore the impact of regulation, notably differentiated capital requirements. It is shown that net worth buffers aligned to the balance sheet total of a node do not enhance stability. However, if higher capital is required in accordance to the amount of interbank assets, significant stabilizing effects are obtained even if the total amount of net worth in the network is kept constant.

Our approach relates to the growing literature which uses network approaches to study financial contagion and systemic risk. Financial network models exist in various forms. Some papers combine a balance sheet approach with a stochastic setting which allows analytical results (e.g. Tasca and Battiston, 2011). Other work empirically describes and analyzes the evolution of banking systems over time (e.g. Hale, 2011). Simulation-based apporaches exist in many variants, too. Some intend to reproduce a real existing banking system as precisely as possible, see, for example, Elsinger et al. (2006) for Austria, or Aikman et al. (2009) and the references therein. This allows to detect potential risk sources and systemically relevant institutions in a specific net, but has to deal with incomplete or inaccurate data. Additionally, such models do not reveal the general relation of network characteristics and contagion risk which is highly relevant to understand systemic risk. Shocks have an extremely complex effect on network stability (Berman et al., 2011). Networks, in particular, may exhibit surprising domino effects due to so called "cascading" effects. Relatively small shocks, which in most cases are easily absorbed by the system, may trigger the breakdown of large parts. This "robust-yet-fragile" nature is well documented for complex systems and known to be related to the level of connectivity (Watts, 2002). Network topology is thus an important factor for contagion effects.

Network models based on random graphs investigate the systematic interplay between network structure, shock transmission mechanisms, and system stability. The models differ in the types of agents and contagion channels. Anand et al. (2011) set up a specific network consisting of domestic banks, international financial institutions and corporates and includes feedback effects which amplify contagion. Georg (2010) additionally includes a central bank and compares different forms of network topology. Teteryatnikova (2010) focuses on "tiered" banking systems and studies whether such structures reduce systemic risk. While modelling a wide variety of structural forms most such models exibit a high degree of regularity. Only recently, authors explicitely try to include inhomogeneities. Both Sachs (2010) and Berman et al. (2011), like our approach, build on the model by Nier et al. (2007). Sachs (2010) introduces inhomogeneities only in the interbank market by constructing a variety of exposure matrices. Simulation results indicate a decrease of the network's stability which is consistent with our results. Berman et al. (2011) mainly concentrate on the definition of a stability measure for the system and the computational complexity to determine this measure. In the course of exploring the algorithm's complexity the paper provides a very detailed analysis of potential feedback effects and the sources of cascades. Caccioli et al. (2011) extend the model by Gai and Kapadia (2010). The inhomogeneities they incorporate consist of heterogeneous degree distributions, heterogeneous balance sheet size and degree correlations between banks. Consistent with our results, they find that inhomogeneity tends to increase systemic risk which is explicitly due to the failure of a well-connected but not an average bank. They also study the role of a better bank capitalization for selected institutions and find that this strategy is successful if big banks are better capitalized but not if only the well-connected ones are targeted. Due to the different modelling approach the role of big banks in their model is similar to those with high interbank activity in ours. These results, therefore, support our finding on the crucial role of banks with high "riskiness". The main advantage of our modelling approach compared to similar efforts is the clear and flexible role of the three "inhomogeneity parameters", which can be chosen independently. The approach also allows for other distributional forms and can easily be combined with additional features of a network model like feedback effects or different agents.

This work is organized as follows: Section II describes the homogeneous model as introduced by Nier et al. (2007) as well as our three proposed model extensions. Our simulation results for the default dynamics are presented in Section III. The question whether or not contagion risks can be reduced by macro-prudential regulatory capital requirements is addressed in Section IV. Section V concludes.

II Addition of heterogeneity to the network model

II.1 Homogeneous network model

The two basic building blocks of the model proposed by Nier et al. (2007) can be outlined as follows: At first, a random graph as introduced by Erdös and Rényi (1959) is constructed in order to describe the underlying financial network. Then, a simplified balance sheet is built up for each network node, consisting of external assets given to ultimate investors, interbank assets, interbank liabilities, deposits, and net worth. The construction scheme thus relies on the following macroeconomic model parameters:

- N, the number of banks in the system,
- p, the probability that two nodes are connected,
- E, the total amount of external assets in the banking system (i.e. E is the sum of all loans given to ultimate investors),
- γ, the ratio of the total net worth to total assets in the system (i.e. the average leverage in the system), and,
- θ, the ratio of interbank assets to total assets in the system (i.e. the fraction of the interbank market).

Note that besides the connection probability p all model parameters could be easily calculated for realistic financial systems if the balance sheets of all banks were known.

Any particular realization of a random graph with N nodes and probability p for all directed edges leads to a certain number Z of actual links in the system. In the next step the simplified balance sheets of the individual banks are populated: The assets of a bank i, denoted by a_i, consist of external assets a_i^{ext}, i.e. the total volume of loans given to ultimate investors, and the borrowings of other banks (interbank assets) a_i^{int},

$$a_i \quad = \quad a_i^{\text{ext}} + a_i^{\text{int}}. \tag{1}$$

On the other hand, liabilities l_i of bank i consist of net worth c_i, costumer deposits d_i and interbank borrowing b_i^{int}

$$l_i \quad = \quad c_i + d_i + b_i^{\text{int}}. \tag{2}$$

Because of balance sheet identity, $a_i = l_i$ holds for all banks $i = 1, \cdots, N$ in the network. Now, the total amount I of interbank assets in the network is homogeneously distributed over the existing directional links as described by the (link independent) weight

$$w \quad = \quad \frac{I}{Z} = \frac{1}{Z}\frac{\theta}{1-\theta}E. \tag{3}$$

All interbank assets a_i^{int} and interbank liabilities b_i^{int} are thus determined. The next step is to distribute the external assets E to the banks. This is done in two steps. First, each bank is assigned an amount $\tilde{a}_i^{\text{ext}}$ according to its net interbank borrowing to ensure that it is able to operate, i.e.,

$$\tilde{a}_i^{\text{ext}} = \max\left(b_i^{\text{int}} - a_i^{\text{int}}, 0\right). \tag{4}$$

To avoid the problem of closing all balance sheet gaps opened up this way, the percentage of external assets must not be set too low. In a second step, the remaining external assets are evenly distributed to all banks. Thus, the resulting amount a_i^{ext} of external assets of bank i can be expressed as

$$a_i^{\text{ext}} = \tilde{a}_i^{\text{ext}} + \frac{1}{N}\left(E - \sum_{j=1}^{N} \tilde{a}_j^{\text{ext}}\right). \tag{5}$$

The net worth c_i of each bank is now determined by the leverage parameter γ as

$$c_i = \gamma\, a_i. \tag{6}$$

The amount d_i of customer deposits can be derived from the balance sheet identity as $d_i = a_i - c_i - b_i^{\text{int}}$. In this way, the construction of the individual balance sheets is completed.

It is important to notice that the construction scheme contains a stochastic component because different network realizations are obtained if the graph is constructed several times. This is due to the fact that two banks are connected only with a certain probability. Despite the deterministic generation of the balance sheets, differences between the network nodes occur in actual model realizations. The results in actual model simulations must therefore be averaged over several network configurations. If the number N_{Sim} of network realizations for the averaging procedure is above 100, the obtained results hardly depend on N_{Sim}. In our simulations we set $N_{\text{Sim}} = 150$.

II.2 Financial shocks and shock transmission

In general, two kinds of financial shocks can be studied within this framework: Correlated shocks affecting all banks at the same time, and idiosyncratic shocks causing primary losses in one bank only. In this work, we study idiosyncratic shocks which are modeled as a loss of amount s_i in the external assets of one particular bank in the system. This loss is initially absorbed by the net worth c_i. If the net worth c_i is not big enough, bank i defaults and the remaining loss, $s_i - c_i$, is transmitted to solvent creditor banks through the interbank liabilities b_i^{int}. It is assumed that all creditor banks have to take equal shares of the transferred losses. Note that customer deposits are assumed to have the highest priority and are only affected if net worth and interbank borrowings are not sufficient to balance the occurred losses. A default of a creditor bank that cannot absorb the transmitted loss will be called a *first round default*. The defaulted (direct) creditor bank will further transfer the still uncovered losses to its own creditor banks. Here, already defaulted creditor banks must not be taken into account. Defaults of creditor banks of the (direct) creditor banks are called *second round defaults*.

The extent of the total effect greatly depends on which particular node is initially shocked. In our simulations, we therefore shock every bank for a given network realization and evaluate the effects. Then, we determine both the average and the worst case of the number of defaulted banks as well as the sum of the balance sheet totals of the defaulted banks ("defaulted balance"). In a second step, all these configuration results are averaged over N_{Sim} configurations.

II.3 Extension to inhomogeneous network nodes

In the following, we propose three extensions to the homogeneous model: First, we implement a node property called connectivity that leads to pair dependent connection probabilities which allows to study the role of well-connected banks. Second, we propose the node property riskiness that leads to pair-dependent (directed) interbank lendings and, in particular, to banks with very disproportionately large interbank assets. And finally, we introduce a non-homogeneous distribution of external assets reflecting different business models.

In order to implement these extensions, we introduce an appropriate type of distribution to model the inhomogeneities, namely a modified normal distribution $\tilde{\mathcal{N}}\left(p;\sigma^2;a;b\right)$: If the quantity $x \sim \mathcal{N}\left(p,\sigma^2\right)$ is normally distributed, the random variable $y_{[a;b;p;\sigma^2]} \sim \tilde{\mathcal{N}}\left(p;\sigma^2;a;b\right)$ is calculated as follows:

$$y_{[a;b;p;\sigma^2]} = \begin{cases} (p-a)\exp(x-p)+a & \text{if } p \geq x \\ (p-b)\exp\left[\frac{p-a}{p-b}(x-p)\right]+b & \text{otherwise} \end{cases} \tag{7}$$

This definition ensures that the random variable $y_{[a;b;p;\sigma^2]}$ is restricted to values within the interval between a and b. For example, by setting $[a;b]=[0,1]$ we can ensure that the whole distribution only takes values between 0 and 1 which is crucial for our model if the values are meant to be probabilities. For the other two inhomogeneities the choice of the interval allows to generate suitable numbers as well. The parameter p shifts the mean of the distribution and represents in our model the average level of the respective quantity (i.e. connectivity, riskiness or external assets) throughout the system. Finally, the parameter σ^2 controls the dispersion of the distribution. In our model, σ^2 allows to characterize the degree of the respective inhomogeneity in the system with a single number, which can be varied continuously. The impact of different

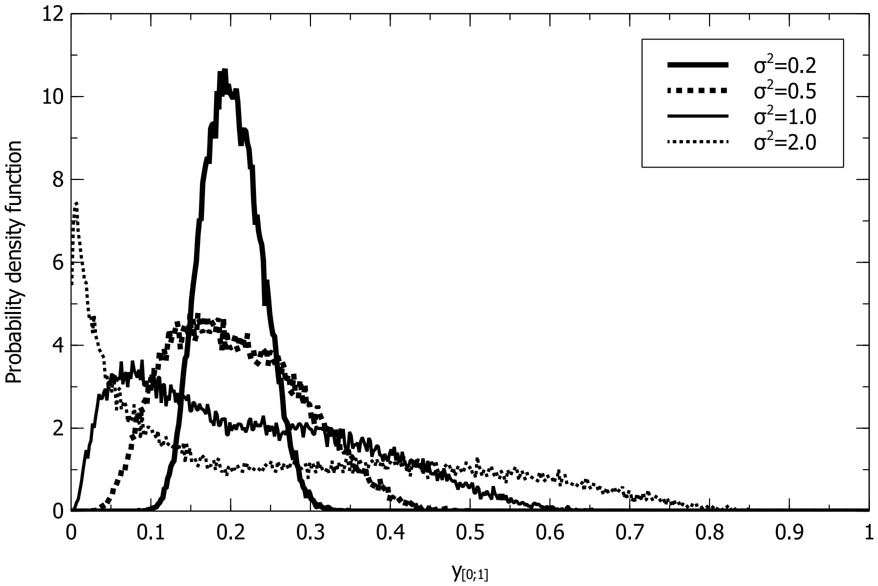

Figure 1: Probability density function of the random variable $y_{[0;1]}$ as defined in Eq. (7) where the mean of the underlying normal distribution is set to $p = 0.2$. The results are based on 50.000 generated random numbers for each value of σ^2.

types and degrees of inhomogeneity on the network stability can thus be easily studied. While not consistent with the rigid statistical definition of the variance of the distribution, σ^2 provides comparable information, so that we refer to it as a variance like quantity. Furthermore, note that both the mapping function in Eq. (7) and its first derivative are continuous at p and the construction based on the normal distribution is very simple and natural.

Actual results for the probability density function of $y_{[0;1]}$ are shown in Fig. 1. As long as σ^2 remains small relative to the interval $[a; b]$, the distribution function looks very similar to a regular normal distribution. If σ^2 is increased the distribution function becomes more and more asymmetric but remains restricted to the chosen interval $[0; 1]$. If σ^2 notably exceeds the width of the interval, a very pronounced maximum at the interval boundary occurs. For parameter values $\sigma^2 \leq 1$, which we use in the following analysis, the family of distributions reflects a wide variety of reasonable, inhomogeneous shapes.

We carefully verified that the homogeneous limit of the model introduced in the following (i.e. the model with all variance like quantities σ^2 set to 0) perfectly resembles the homogeneous model as considered by Nier et al. (2007). We also verified that the introduced inhomogeneities indeed produce significant variations in node degrees, total assets (size of the bank) and net interbank positions. Results are presented in the appendix.

II.3.1 Inhomogeneity due to connectivity

In order to introduce inhomogeneous connection probabilities, we initially define a node-dependent inner connectivity u_i by using the restricted normal distribution introduced above,

$$u_i \quad \sim \quad \tilde{\mathcal{N}}\left(p^*; \sigma_p^2; 0; 1\right). \tag{8}$$

The parameter p^* has to be chosen such that the number of network connections Z is the same as in the corresponding homogeneous model (see discussion below). Note that connectivity is at first defined as an attribute of nodes i not edges ij. The resulting connection probability p_{ij} that bank i has lent bank j some funds is derived from the pair of connectivities u_i and u_j as follows[2],

$$p_{ij} \quad = \quad \sqrt{u_i \cdot u_j}. \tag{9}$$

Thus, if all connectivities u_i are set to the constant probability p the connection probability of the homogeneous model is obtained. An increasing σ_p^2 leads to a broader distribution of the conncetivities u_i in the system, and for the connection probabilities p_{ij} as well.

The choice of p^* needs to take into account that the number of links Z varies for different network configurations. The requirement that Z equals the homogeneous case for constant connection probability p can only hold for the expectation value. The expected number of edges in the inhomogeneous model, $\langle Z(p^*)\rangle$, must be equal to the expected number of (directed) links in the homogeneous model, $N(N-1)\cdot p$, i.e.

$$\langle Z(p^*)\rangle \quad = \quad N(N-1)\cdot p. \tag{10}$$

For a given p, an approximate value for p^* must be determined numerically. In the appendix we provide further information and results for p^*.

II.3.2 Inhomogeneity due to riskiness

In the homogeneous model, the interbank assets are equally distributed over all network links. In conjunction with a constant connection probability, only moderate net interbank lending or borrowing can occur. To allow varying link weights in the network, the amount w_{ij} of funds lent by creditor bank i to network node j is assumed to depend on an inner property of the network nodes which we call riskiness. Riskiness is interpreted as follows: A network node i with high riskiness v_i has a tendency on the interbank market to lend rather high amounts to single creditor banks. At the same time, an interbank refinancing based on small quantities is

[2] The definition of the restricted distribution ensures that the inner connectivity u_i is restricted to values between 0 and 1 so that Eq. (9) always provides useful values for the connection probabilities p_{ij}.

accepted. In this way, the model provides banks with high *net* interbank borrowing or lending, and inhomogeneities in balance sheet construction are enhanced. To model riskiness, we again use the restricted normal distribution as introduced above:

$$v_i \quad \sim \quad \tilde{\mathcal{N}}(0.5, \sigma_w^2; 0; 1). \tag{11}$$

The variance-like quantity σ_w^2 again determines the degree of inhomogeneity, the limit $\sigma_w^2 = 0$ resembles the homogeneous model. Based on the nodes' riskiness values, we define the (non-constant) weights of network links with the following equation[3]:

$$w_{ij} \quad = \quad \frac{Z_{ij}\, v_i\, (1 - v_j)}{\frac{1}{Z} \sum_{i,j} Z_{ij}\, v_i\, (1 - v_j)}\, w \tag{12}$$

where w denotes the link weight of the homogeneous model and Z_{ij} the linkage function

$$Z_{ij} \quad = \quad \begin{cases} 1 & \text{if network link exists in the configuration} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

When two nodes with very different riskiness are linked, a high value of w_{ij} is combined with a very low value of w_{ji}, indicating a high net position. The risky node tends to be large in terms of total assets. On the other hand, nodes with average riskiness are linked by medium weights. The denominator of the right hand side of Eq. (12) ensures a constant total weight $\sum_{i,j} w_{ij}$ of network links in the system for any actual values v_i of the riskiness. The results of the inhomogeneous model are therefore comparable to those of the corresponding homogeneous network.

II.3.3 Inhomogeneous distribution of external assets

Finally, a non-homogeneous distribution of the external assets is introduced to reflect the role of big financial institutions focusing on wholesale and retail. For this purpose we add a node propery α_i to Eq. (5) which could be called "external activity" because it determines the amount of external assets that are assigned to the node. Thus, Eq. (5) is replaced by:

$$a_i^{\text{ext}} \quad = \quad \tilde{a}_i^{\text{ext}} + \alpha_i \cdot \frac{1}{N} \left(E - \sum_{j=1}^{N} \tilde{a}_j^{\text{ext}} \right). \tag{14}$$

[3]The definition of the restricted distribution ensures that the riskiness is restricted to values between 0 and 1 so that Eq. (12) always leads to positive weights of the network links. The limit $\sigma_w^2 = 0$ resembles the homogeneous model because the distribution of the riskiness is centered at point 0.5.

The external activities α_i are again modelled by the restricted normal distribution

$$\alpha_i = \frac{\tilde{\alpha}_i}{\frac{1}{N}\sum_{j=1}^{N}\tilde{\alpha}_j}, \tag{15}$$

$$\tilde{\alpha}_i \sim \tilde{\mathcal{N}}\left(1, \sigma_E^2; 0; +\infty\right). \tag{16}$$

Note that due to the restricted distribution[4] in Eq. (16) the external activity can not fall below 0, and the net interbank borrowings of a bank can never exceed its external assets [see (4) for $\tilde{a}_i^{\text{ext}}$]. The denominator in Eq. (15) ensures a constant value E for the total amount of the external assets. Furthermore, the limit $\sigma_E^2 = 0$ resembles the homogeneous model. The results of the inhomogeneous model as discussed here can thus be compared to those of the corresponding homogeneous network.

III Simulated default dynamics

This section presents the simulation results for the inhomogeneous network model introduced above. We use the benchmark model parameters as summarized in Tab. 1. These are identical to the parameters studied by Nier et al. (2007) exept for the number of banks N. Due to a very efficient model implementation, much larger networks are studied in this work: We have performed simulations for systems with up to 250 banks, while Nier et al. (2007) considered networks with 25 nodes only. In this way we were able to check the finite size effects. In order to ensure that the results obtained for networks of different sizes are comparable, the connection probability p must be adjusted in order to keep the average number of network links per node constant. If the product of N and p is fixed at a given value, a very moderate impact of the system size on the simulation results is observed for networks between 25 and 250 nodes.

The simulated default dynamic is analyzed with respect to the three qualitative model characteristics. These are the bank capitalization (modelled by the percentage of net worth to total assets, γ), the connectivity [modelled by the (average) connection probability, p], and the fraction of the interbank market (modelled by the percentage of interbank assets to total assets, θ). For all three perspectives we will particularly discuss the impact of inhomogeneities on the network stability.

III.1 Bank capitalization

In order to study the influence of bank capitalization on the stability of financial networks, we vary the net worth level γ in our model and keep all other parameters constant. The

[4]Only negative values for the external activity must be excluded. No upper bound of the restricted distribution has therefore been chosen. The center of the distribution is set to 1 so the values for the the volatility σ_E^2 can be compared to those of the new model parameters σ_p^2 and σ_w^2 introduced above.

Parameter	Description	Value
E	Total amount of external assets	100000
N	Number of banks in the network system	100
p	Probability of a connection between two nodes	0.05
θ	Percentage of interbank assets to total assets	20%
γ	Percentage of net worth to total assets	$0 \cdots 8\%$
N_{Sim}	Number of configurations used for averaging	150

Table 1: Benchmark model parameters for the simulations presented in this work.

homogeneous limit is obtained if the three parameters, σ_p^2, σ_w^2, and σ_E^2, related to the model extensions introduced in this work, are set to 0. As one can see in Fig. 2, the number of contagious defaults increases as expected if the total net worth is decreased. However, the well-defined structure of the observed function is quite remarkable. Only at high net worth level, the bank facing the initial loss defaults because the transmitted part of the shock can be absorbed by its creditor banks. Decreasing the net worth level γ to a critical value of about 4.5%, contagious defaults of creditor banks start to occur and the total number of defaults increases. The very flat region for net worth levels between 1.5% and 3.5% can be explained by first round defaults - all creditor banks of the bank facing the initial shock default - where the level of net worth ensures that no further defaults (i.e. no second round defaults) occur. Note that the approximately 6 defaults observed on average in this flat region directly correspond to the model parameters: The bank suffering the initial loss has approximately $p \cdot (N-1)$ creditor banks so that one would expect $0.05 \cdot 99 + 1 = 5.95$ defaults if no second round defaults occur. If the net worth level γ is further decreased below 1.5% the number of defaults dramatically increases because second round defaults occur. In this way, the whole network becomes unstable and collapses.

If the *connectivity distribution* is broadened by positive values of σ_p^2, big and well-connected banks emerge. Surprisingly, as one can see from Fig. 2, this inhomogeneity slightly stabilizes the network almost within the whole parameter range if the number of defaults is considered. Only if the net worth parameter γ is between 4.5% and 6% the number of defaults is enhanced on a very low level. The same effect is obtained if the defaulted balance is considered. However, as one can see in panel (a) of Fig. 3, the situation completely changes if one looks at the defaulted balance of the worst case scenario. The results for the defaulted balance here clearly show that well-connected banks can significantly enhance the risks of a complete breakdown of the system for (rather low) net worth levels below 3%.

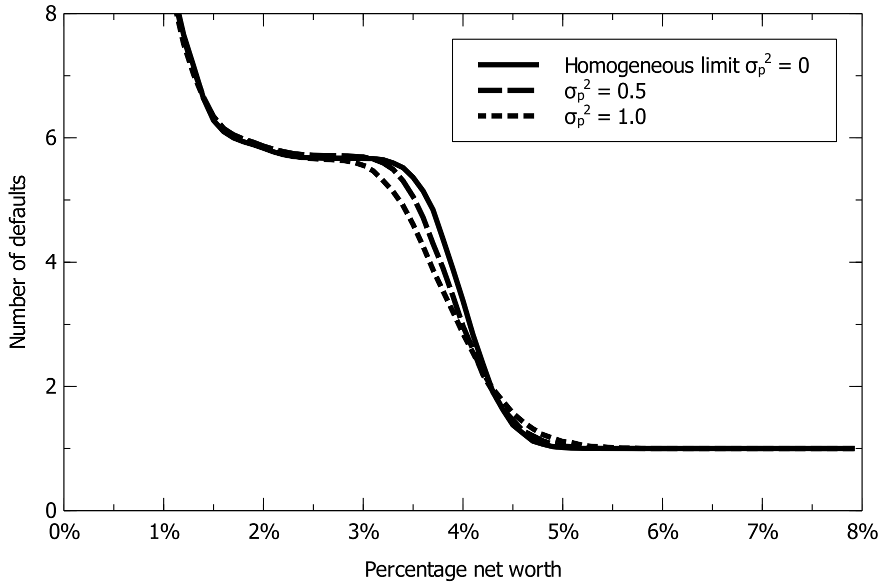

Figure 2: Impact of the connectivity on the number of defaulted banks as a function of the net worth parameter γ. The parameters are taken from Tab. 1, σ_w^2 and σ_E^2 are set to 0.

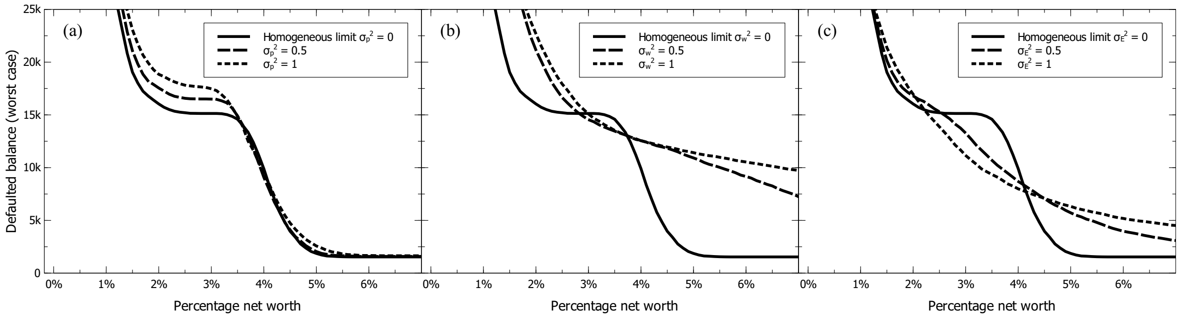

Figure 3: Impact of system inhomogeneities on the defaulted balance in the worst case scenario as a function of the net worth parameter γ: Inhomogeneity due to connectivity is included in panel (a), the concept of riskiness is enabled in panel (b), and the effect of an inhomogeneous distribution of external assets is shown in panel (c). The model parameters are taken from Tab. 1.

As one can see in panel (b) of Fig. 3, the introduction of a *riskiness distribution* due to a positive value for σ_w^2 has a much stronger effect on the simulation results: First, the well-defined structure found for the homogeneous limit is completely washed out. And second, the defaulted balance in the worst case scenario is significantly increased for almost all net worth levels γ. At this point it is important to recall the effect of riskiness on the properties of the network nodes: Banks with a high riskiness have a tendency to an unbalanced behavior on the interbank market, they lend rather high amounts to single borrower banks. And, at the same time, these banks accept an interbank refinancing based on small quantities. A finite riskiness distribution thus leads to banks with disproportionately large interbank assets. Our results clearly show that such banks accelerate contagion effects and, therefore, significantly destabilize financial networks.

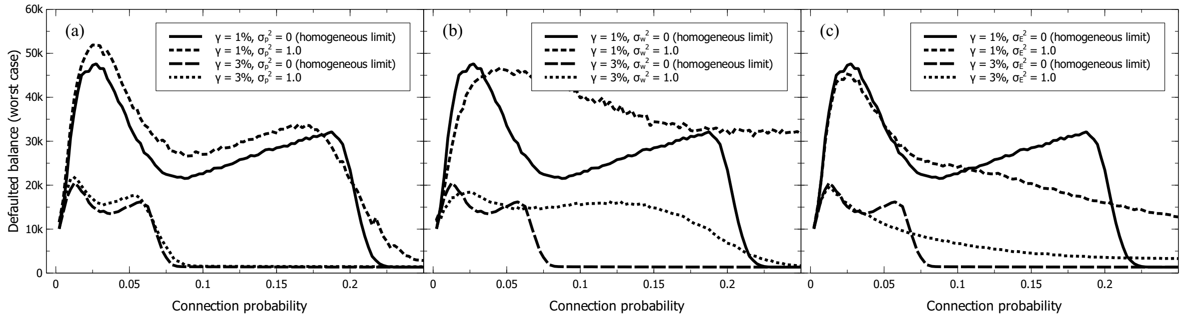

Figure 4: Impact of system inhomogeneities on the defaulted balance in the worst case scenario as a function of the connection probability p: Inhomogeneity due to connectivity is included in panel (a), the concept of riskiness is enabled in panel (b), and the effect of an inhomogeneous distribution of external assets are shown in panel (c). The model parameters are taken from Tab. 1.

In comparison to the riskiness, the implementation of a *distribution of external assets* due to positive values for σ_E^2 has rather moderate effects on the simulation results for the default dynamics. The well-defined structure of the function is mainly washed out, but a general destabilizing impact is not observed: As on can see in panel (c) of Fig. 3, for net worth levels above 4% the defaulted balance in the worst case scenario is slightly enhanced. At the same time we observe small stabilizing effects for net worth levels γ between 2% and 4%. As already mentioned in Section II.3.3, an unequal distribution of the external assets leads to network nodes with high amounts of external assets that can be interpreted as big banks focusing on wholesale and retail customers. In general, we can conclude that the mix of business models is diversified by positive values of σ_E^2. It is important to notice that the stability of the network as a whole is barely affected by this source of system inhomogeneities.

III.2 Connectivity

We consider the defaulted balance as a function of the connection probability p while the other model parameters are kept constant. In case of the homogeneous limit we observe the well-known, characteristic M-like structure (see Fig. 4). Two interacting mechanisms describe how network links affect the system stability: On the one hand, more network connections are more channels to transmit shocks from bank to bank enabling contagious defaults. On the other hand, a higher number of links also means that more banks are involved to cover the occured losses by their net worth. Hence, links are both, shock transmitters as well as shock absorbers as already pointed out by Čihák et al. (2011). Which role prevails depends on the connection probability. For very low values of the p, additional links increase contagious defaults at neighbouring banks until the risk sharing effect sets in. At the inner minimum of the M-like structure only the direct creditor banks of the bank affected by the initial shock get defaulted, i.e. no second round defaults occur. If the connection probability p is further enhanced the shock transmission effect again becomes dominant leading to an increasing number of defaults. This effect is caused by amplified first round effects due to a growing number of direct creditor banks. Finally, for high values of p, contagious defaults are reduced again due to the shock absorbing effect. As one can see in Fig. 4, the M like structure is stretched or shortened by the net worth parameter γ. However, the general mechanisms behind the observed default dynamic are not dependent on the actual net worth level γ.

If we introduce a broadened *connectivity distribution* the results only moderately vary [see panel (a) of Fig. 4]. As already observed in Section III.1, the implementation of a *riskiness distribution* (as enabled by a positive σ_w^2) has a much more pronounced effect, as one can see in panel (b) of Fig. 4: While the behavior is barely affected for low connection probabilities, the shock absorbing abilities of the system are significantly weakened in the parameter range of dominating first round defaults. Subsequently, a strongly increased defaulted balance in the worst case scenario is observed in a wide parameter range.

A quite interesting behavior is found if a *distribution of external assets* is implemented by setting σ_E^2 to a positive value. Here, as one can see in panel (c) of Fig. 4, the well-defined maximum for low connection probabilities p remains almost unchanged. The parameter range of dominating first round defaults is however completely flattened. Note that this is caused by a very obvious mechanism triggered by σ_E^2: If a big bank focusing on wholesale and retail customers is the subject of the initial shock high amounts of external assets are assumed to be defaulted which must be absorbed by the network. Having in mind the restricted number of direct creditor banks it is very probable that second and third round effects occur. The transition region of the M like structure is therefore extremely extended.

III.3 Interbank exposure

Finally, the role of the interbank assets is investigated. For this purpose the number of defaulted banks is considered as a function of the ratio θ of interbank assets to total assets (while the other model parameters are kept constant). Because the absolute amount E of external assets in the system is unchanged, an increase of interbank assets also leads to an increased amount of net worth in the system due to the constant ratio γ. The model parameter θ this changes the relation between interbank assets and external assets but does not affect the net worth level of the network nodes. Because the number of network links is kept constant a variation of θ directly affects the link weight w: As one can see in Eq. (3), an increasing θ leads to an increasing link weight w, too.

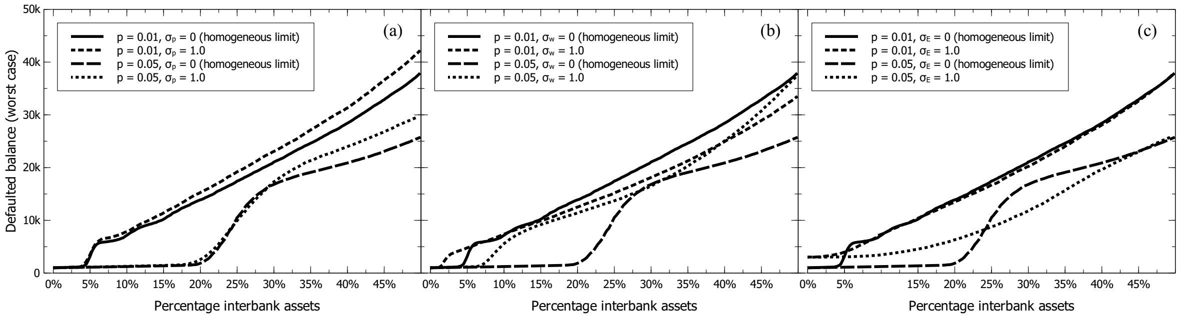

Figure 5: Impact of system inhomogeneities on the defaulted balance in the worst case scenario as a function of the fraction θ of interbank assets in comparison to the total balance: Inhomogeneity due to connectivity is included in panel (a), the concept of riskiness is enabled in panel (b), and the effect of an inhomogeneous distribution of external assets are shown in panel (c). The model parameters are taken from Tab. 1.

In the case of the homogeneous limit, Fig. 5 shows hardly any defaults for low values of θ. The initial shock is barely transmitted to the creditor banks because the link weight w is too low. However, if the ratio of interbank assets to total assets is increased above a critical value defaults of creditor banks and an increased defaulted balance are observed. Nevertheless, the number of defaults and the defaulted balance in the system remain restricted even for very high values of θ. This is due to the fact that the occurred losses within the external assets (of the bank facing the initial shock) are absorbed by raising net worth amounts of the first bank (directly affected by the shock) and their creditor banks.

As one can see in panel (a) of Fig. 5, only minor changes of the results are obtained if a *connectivity distribution* leading to pair-dependent connection probabilities is implemented in the system (i.e. non-zero values for σ_p^2 are chosen). As already observed in Sections. III.1 and III.2, a broad *riskiness distribution* (as implemented in the system by positive values for σ_w^2) leads to more significant effects in the simulated defaulted balance as shown in panel (b) of Fig. 5. On one hand, for small θ values the parameter range of very low defaulted balances is strongly reduced. On the other hand, the defaulted balance is enhanced for almost all θ values if moderate or rather high connection probabilities are chosen. This observation again underlines our very important finding that banks with disproportionately large interbank assets significantly increase contagion risk in the financial network. Finally, as one can see in panel (c) of Fig. 5, very different effects on the simulated default dynamics are observed if an inhomogeneous *distribution of external assets* is implemented (i.e. positive values for σ_E^2). The step-like structure obtained for the homogeneous limit is almost completely washed out. Note that such a structure-flattening effect has also been found with respect to bank capitalization and connectivity properties as discussed in Section III.1 and III.2. Another interesting effect is observed for low θ values: In this parameter range only the network node suffering from the initial shock defaults because only small losses are transmitted to the creditor banks. Nevertheless, the defaulted balance in the worst case scenario is enhanced because an inhomogeneous distribution of external assets leads to big banks with high amounts of external assets, which dominate the worst case scenario.

IV Regulatory response

This section picks up the central question whether and how the system stability can be efficiently improved by regulatory measures. The kind of network models discussed in this work controls the leverage (net worth) in the system by a specific parameter, γ, and is, therefore, especially suited for an analysis of capitalization effects. Naturally, a higher net worth level γ will enhance the system stability. However, equity capital is economically costly. We discuss the more relevant question: Can the system's resilience be strengthened by a suited reallocation of net worth within the network while the total amount of capital is kept constant? For this purpose, a parametrized node-dependent net worth level is introduced and studied. This node-dependent net worth distribution is assumed to be a result of regulatory requirements. Below we study and compare two possible approaches. At first, the idea that size matters is implemented by means of a size dependent net worth distribution. We will however see that this approach is not able to stabilize the system in the case of idiosyncratic shocks. A second approach will turn out to be more successful: a node-dependent net worth level related to a node's interbank assets.

IV.1 Size-dependent net worth distribution

A node-dependent net worth level γ_i is introduced by rewriting Eq. (6) which defines each bank's capital as a fixed fraction γ of its total assets as $c_i = \gamma_i a_i$. The new parameters γ_i replace the previously constant capitalization level γ. They are defined by a function of the relative node size,[5] where size is measured by the total assets a_i of a bank. An additional new parameter f_{size} is introduced which is meant to tune the size-dependence of this model extension. The higher f_{size} the more should the bank's capital vary with its relative size $\frac{a_i-\bar{a}}{\bar{a}}$. Accordingly, we define γ_i as a function of $(f_{\text{size}}\frac{a_i-\bar{a}}{\bar{a}})$. For simplicity, we assume an exponential dependence

$$\gamma_i \quad = \quad f_{\text{norm}} \cdot \exp\left[f_{\text{size}} \frac{a_i - \bar{a}}{\bar{a}}\right]. \tag{17}$$

Here, the factor

$$f_{\text{norm}} \quad = \quad \frac{\gamma \sum\limits_i a_i}{\sum\limits_i a_i \, \exp\left[f_{\text{size}} \frac{a_i - \bar{a}}{\bar{a}}\right]} \tag{18}$$

[5]Note that the model construction does not take advantage of a constant percentage of net worth to total assets. The previous model construction is thus not affected by this model extension.

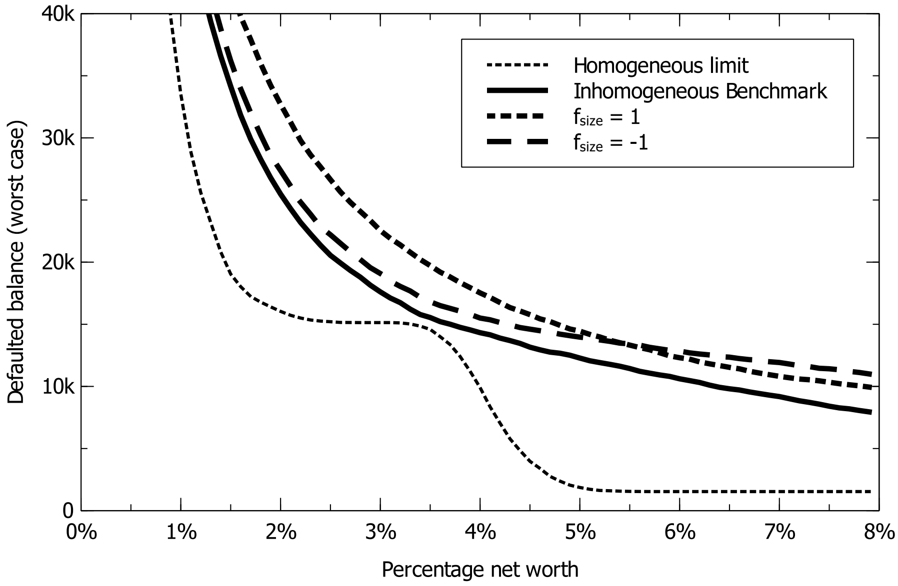

Figure 6: Impact of a size-dependent net worth distribution on the defaulted balance in the worst case scenario. The simulation results are shown as a function of the net worth level γ where the model parameters are taken from Tab. 1. The additional parameters σ_p^2, σ_w^2, and σ_E^2 for the model extensions introduced in this work are set to 0 (1) for the homogeneous limit (inhomogeneous benchmark).

ensures that the ratio of total net worth to total assets in the system is kept constant at level γ, independent of the actual value for f_{size}. If f_{size} is set to 0 a constant net worth level is chosen for all network nodes which means identical capital requirements for all banks. Positive (negative) values for f_{size} imply higher (lower) net worth levels for big banks, i.e. an additional capital charge.

In order to discuss the impact of the newly introduced size-dependent net worth distribution on the simulated default dynamics, we consider a particular model representation which we call *inhomogeneous benchmark*. In this case, all three model extensions introduced in this work are combined by setting the variance like parameters σ_p^2, σ_w^2, and σ_E^2 to 1 while the other model parameters are taken from Tab. 1. At this point, we do not want to discuss the properties of the inhomogeneous benchmark in detail. Bearing in mind the diversity of real financial networks, however, we want to consider a reasonable network model with as many sources of inhomogeneities as possible to study financial regulation. With respect to the combined impact of the inhomogeneous model extensions, we verified that only very few (if any) interactions between the concepts of connectivity, riskiness, and inhomogeneous distribution of the external assets occur (see the discussion in the appendix). Accordingly, the (worst case) defaulted balance for the inhomogeneous benchmark is above the results for the homogeneous limit in nearly the complete parameter space (see Fig. 6).

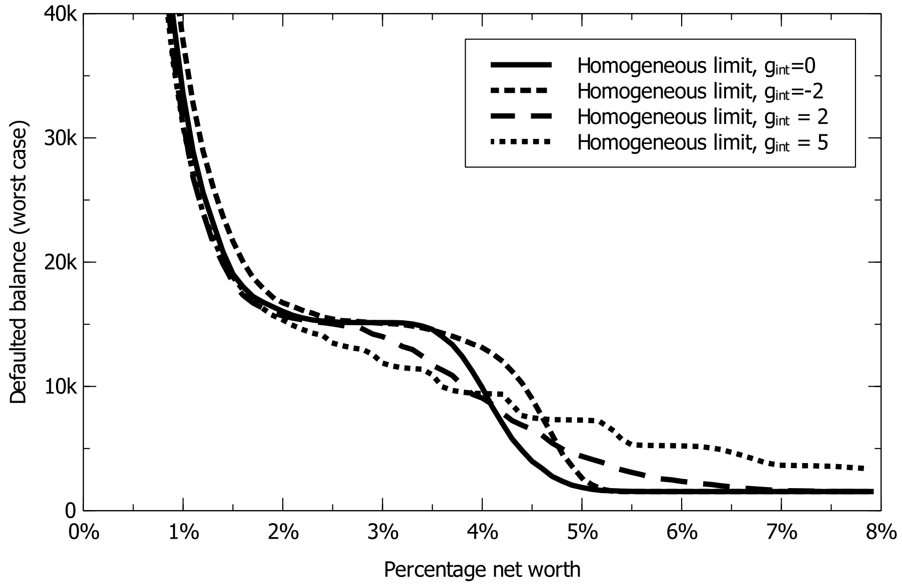

Figure 7: Impact of net worth buffers for interbank exposures on the defaulted balance of the worst case scenario where the simulated default dynamic is shown as a function of the net worth parameter γ. The parameters are taken from Tab. 1, σ_p^2, σ_w^2, and σ_E^2 are set to 0.

For the inhomogeneous benchmark the question whether or not a size-dependent net worth distribution is able to stabilize the network is answered by Fig. 6. A non-zero value for the parameter f_{size} leads to a higher value of the (worst case) defaulted balance for all levels of net worth. Hence, at least within our network model, a regulatory guideline only focusing on bank size is not able to improve the stability of a financial system.

IV.2 Interbank assets and net worth buffers

Our previous analysis indicated inequalities in the distribution of interbank assets as a major source of contagious defaults and system instability. A node-dependent net worth level is hence proposed which is directly related to the interbank assets in the balance sheet,

$$\gamma_i = g_{\text{norm}} \cdot \exp\left[g_{\text{int}}\left(\frac{a_i^{\text{int}}}{a_i} - \theta\right)\right]. \tag{19}$$

The parameter g_{int} controls the effect and allows to reduce the net worth level for banks with a lower proportion of interbank assets and to build up additional capital buffers for banks that are more vulnerable with respect to losses in their interbank assets. The factor

$$g_{\text{norm}} = \frac{\gamma \sum_i a_i}{\sum_i a_i \exp\left[g_{\text{int}}\left(\frac{a_i^{\text{int}}}{a_i} - \theta\right)\right]} \tag{20}$$

in Eq. (19) ensures that the ratio of total net worth to total assets in the system is kept constant at level γ independent from the actual value for g_{int}.

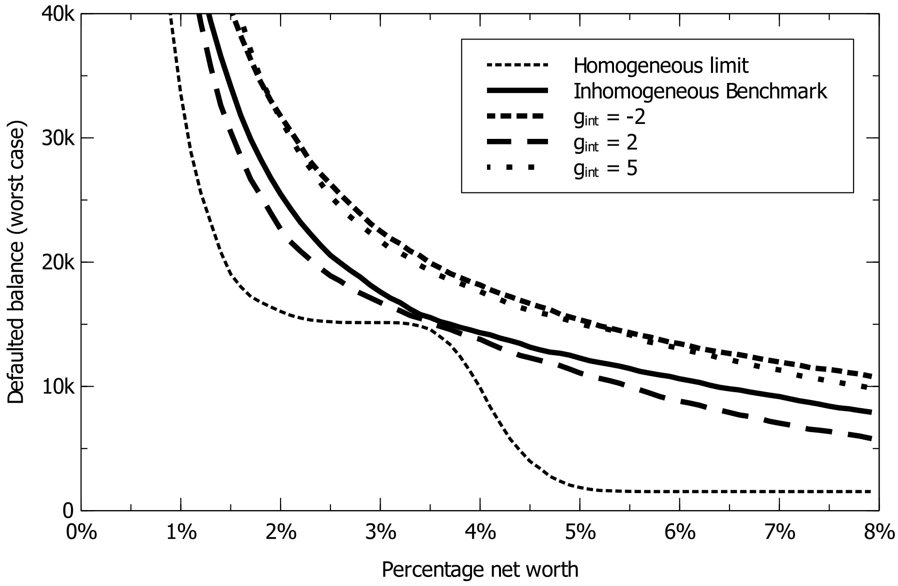

Figure 8: Impact of net worth buffers for interbank exposures on the defaulted balance of the worst case scenario where the simulated default dynamic is shown as a function of the net worth parameter γ. The parameters are taken from Tab. 1, σ_p^2, σ_w^2, and σ_E^2 are set to 0 (1) for the homogeneous limit (inhomogeneous benchmark).

As expected, the effects of the proposed net worth buffers are rather small for the homogeneous limit (see Fig. 7). We just observe a flattening of the structures in the plot. As one can however see in Fig. 8, a stabilizing effect is obtained if the inhomogeneous benchmark is considered (see the line for $g_{int} = 2$). A negative g_{int} has the opposite effect and lowers the capital of those banks which are highly active in the interbank market. This causes a higher system instability which supports the effectiveness of the measure. If the parameter g_{int} is chosen too high ($g_{int} = 5$) an insufficient capitalization of the banks with low interbank exposure countervails the stablizing effect. Overall we find that a differentiated capitalization which addresses the inhomogeneities in the interbank market efficiently reduces contagious defaults. This is especially remarkable as the stabilizing effect is achieved purely by a suited redistribution of equity capital within the system. The total amount of the net worth in the network is strictly kept constant.

V Conclusions

The network model proposed by Nier et al. (2007) offers due to its sparse, parameter-based modeling approach a convenient and efficient environment to study the impact of network characteristics on contagion and system stability. However, the purely homogeneous setup which is clearly unrealistic seriously restricts the model's generality and explanatory power. In this work we have introduced three model extensions which reflect important heterogeneities as found in

σ_p^2	$\overline{p^*}$	$\sqrt{\overline{(p^* - \overline{p^*})^2}}$	$\overline{Z}$	$\sqrt{\overline{(Z - \overline{Z})^2}}$
0	0.050	0.0002	493	22
0.2	0.050	0.0002	494	24
1.0	0.049	0.0002	485	33
2.0	0.047	0.0002	488	63
5.0	0.037	0.0002	494	106
10.0	0.025	0.0002	494	97

Table 2: Accuracy of the determination of the adjusted connection probabilities p^* for different values of the variance σ_p^2 of the inner connectivity. The model parameters are taken from Tab. 1 where the net worth level γ is set to 3%. The variance parameters σ_w^2 and σ_E^2 are set to 0 because they do not affect the determination of p^*. For every parameter set, p^* has been calculated 100 times.

the real world: Well-connected banks are implemented in the network by means of a new node property called connectivty. A second new node property called riskiness is proposed in order to model banks with a disproportionately large amount of interbank assets. And finally, big financial institutions focusing on wholesale and retail customers are integrated by an inhomogeneous distribution of external assets.

The extended network model is used to investigate the default dynamics of financial systems. The simulation results focus on contagious defaults dependent on the three basic model parameters bank capitalization, general connectivity, and interbank exposure. We thus identified the effects of system inhomogeneities on network stability: Whereas well-connected banks as well as big financial institutions focusing on wholesale and retail customers only have a modest impact on default dynamics, we find significantly enhanced contagion risks if banks with disproportiponately large interbank assets are implemented in the network.

Finally, we show that the contagion risks can be reduced by macro-prudential regulatory capital requirements - without a raise in general net worth level: Additional net worth buffers for interbank assets stabilize the network whereas a plain size-dependent capital rule tends to even enhance contagion risks. These findings underline the highly destabilizing role of banks with disproportionate large interbank assets.

Appendix

Determination of the adjusted connection probability p^*. While riskiness and the inhomogeneous distribution of the external assets can be implemented in a deterministic way, the introduction

σ_p^2	σ_w^2	σ_E^2	$\overline{l_i}$	$\max l_i$	$\min l_i$	$\sqrt{\overline{\left(l_i - \overline{l_i}\right)^2}}$	$\sqrt{\overline{\left(a_i^{\text{int}} - \overline{a_i^{\text{int}}}\right)^2}}$	$\sqrt{\overline{\left(b_i^{\text{int}} - \overline{b_i^{\text{int}}}\right)^2}}$
0	0	0	1250	1712	982	99	111	109
1	0	0	1250	1867	925	139	140	140
0	1	0	1250	2460	869	184	196	193
0	0	1	1250	4668	96	640	111	109
1	1	0	1250	2554	853	224	218	218
1	0	1	1250	5351	113	651	140	140
0	1	1	1250	4746	88	614	196	193
1	1	1	1250	4932	73	627	218	218

Table 3: Influence of the model extensions on the balance sheet distribution where the notation of total liabilities l_i of bank i from Eq. (2) is used. The model parameters are taken from Tab. 1 where the net worth level γ is set to 3%. Furthermore, 150 network configurations have been considered for every parameter set.

of the node property connectivity depends on a technical parameter, the adjusted connectivity probability p^*. In order to ensure a stable model evaluation, this parameter (which is only defined via an expected value) must be determined in a reliable way. An iterative numerical approach has been implemented in order to determine p^*: We start with an estimated value for p^*. The number of network links Z is calculated for up to 10.000 configurations generated for p^*. Then, the average of the observed Z values is interpreted as the expectation value of the left hand side of Eq. (10). These two steps are performed within a secant-like method to adjust p^* so that, finally, Eq. (10) holds approximately.

Tab. 2 shows our approximated values for the adjusted connection probability p^* for different levels of σ_p^2. Note that for the chosen model parameters the targeted value for the expected number of links is 495. The small variations of p^* and Z indicate that p^* is determined with high accuracy even if the variance σ_p^2 exceeds the width of the reasonable interval $[0; 1]$.

Interplay of the three model extensions. Tab. 3 presents the network's balance sheet distribution for different combinations of the model extensions. First of all, this shows that the model extensions indeed enhance the inhomogeneities in the system: All three newly implemented concepts clearly broaden the distribution of total assets within the network. The most pronounced effect is observed for the inhomogeneous distribution of external assets.

We find that the network inhomogeneities can be further enhanced if the three proposed model extensions are combined. A node connectivity (enabled by a non-zero value for σ_p^2) hardly interferes with the concepts of riskiness or an inhomogeneous distribution of external assets. There seems to be a competition between the latter two: The broadening of the balance sheet distribution caused by σ_E^2, i.e. by the inhomogeneous distribution of the external assets, is slightly reduced if the riskiness is enabled by σ_w^2. This effect can be understood if one recalls condition (3) that keeps all banks in the network operable. Therefore, as one can see from Eq. (14), only the the external assets left over and are is not assigned by Eq. (4) can be subject of the inhomogeneous distribution enabled by σ_E. The concept of riskiness now leads to banks with disproportionately large interbank assets so that a bigger fraction of the external assets E is already assigned due to condition (3) and the effects of the inhomogeneous distribution of the external assets are, therefore, reduced.

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