Australian National University

Crawford School of Public Policy

CAMA

Centre for Applied Macroeconomic Analysis

Exchange rate shocks in multicurrency interbank markets

CAMA Working Paper 44/2021
May 2021

Pierre L. Siklos
Department of Economics, Wilfrid Laurier University
Centre for Applied Macroeconomic Analysis, ANU

Martin Stefan
Department of Economics, Westfälische Wilhelms-Universität

Abstract

We simulate the impact on the nonbank liabilities of banks in a multiplex interbank environment arising from changes in currency exposure. Currency shocks as a source of financial contagion in the banking sector have not, so far, been considered. Our model considers two sources of contagion: shocks to nonbank assets and exchange rate shocks. Interbank loans can mature at different times. We demonstrate that a dominant currency can be a significant source of financial contagion. We also find evidence of asymmetries in losses stemming from large currency depreciations versus appreciations. A variety of scenarios are considered allowing for differences in the sparsity of the banking network, the relative size and number of banks, changes in nonbank assets and equity, the possibility of bank breakups, and the dominance of a particular currency. Policy implications are also drawn.

Keywords

Systemic risk, financial contagion, interbank markets, multilayer networks

JEL Classification

Address for correspondence:

(E) cama.admin@anu.edu.au

ISSN 2206-0332

The Centre for Applied Macroeconomic Analysis in the Crawford School of Public Policy has been established to build strong links between professional macroeconomists. It provides a forum for quality macroeconomic research and discussion of policy issues between academia, government and the private sector.

The Crawford School of Public Policy is the Australian National University's public policy school, serving and influencing Australia, Asia and the Pacific through advanced policy research, graduate and executive education, and policy impact.

Exchange rate shocks in multicurrency interbank markets

Pierre L. Siklos [a] Martin Stefan [b]

April 29, 2021

Abstract

We simulate the impact on the nonbank liabilities of banks in a multiplex interbank environment arising from changes in currency exposure. Currency shocks as a source of financial contagion in the banking sector have not, so far, been considered. Our model considers two sources of contagion: shocks to nonbank assets and exchange rate shocks. Interbank loans can mature at different times. We demonstrate that a dominant currency can be a significant source of financial contagion. We also find evidence of asymmetries in losses stemming from large currency depreciations versus appreciations. A variety of scenarios are considered allowing for differences in the sparsity of the banking network, the relative size and number of banks, changes in nonbank assets and equity, the possibility of bank breakups, and the dominance of a particular currency. Policy implications are also drawn.

Keywords: Systemic risk, financial contagion, interbank markets, multilayer networks

---

[a] Department of Economics, Wilfrid Laurier University, Centre for Applied Macroeconomic Analysis (CAMA)

[b] Corresponding author: Department of Economics, Westfälische Wilhelms-Universität Münster, Am Stadtgraben 9, 48143 Münster, Germany, E-mail: Martin.Stefan@hotmail.de

We would like to thank the editor and three anonymous referees for their helpful comments and suggestions.

1 Introduction

Most, if not all, banking crises have their roots in cheap credit, overconfident investors and lax regulation. What serve as the triggers and contagion mechanisms, however, vary widely. Therefore, a sizeable literature on systemic risk in interbank markets has emerged. Researchers first modeled these markets using simple interbank lending matrices in which banks are linked through a network of bilateral exposures (see Upper 2011, and the references therein). More recently, researchers have started to model interbank markets as multiplex networks. In these networks, financial institutions are linked to one another through multiple layers of different subnetworks. These different layers can, for example, pertain to different asset classes (Poledna et al. 2015), different maturities (Gabrieli & Salakhova 2019) or both (Bargigli et al. 2014, Aldasoro & Alves 2018).[1] In this sense, banks do not engage with one another in a single market. Instead, banks are connected to one another across different markets, i.e., markets for long-term assets vs. markets for short-term assets or markets for deposits and loans vs. markets for derivatives.

In this paper, we develop a simple framework in which financial institutions are connected to each other via currency exposures. In doing so, we are able to model one of the most notorious sources of financial contagion: exchange rate shocks. In his 2011 literature review, Upper concludes that existing work suffers from "an exaggerated focus on scenarios involving the idiosyncratic failure of an individual bank rather than common shocks" (Upper 2011, p. 121). Such truly idiosyncratic failures are, however, very rare. The literature frequently points to the bankruptcies of Barings Bank and Drexel Burnham Lambert. Ironically neither of these failures triggered any significant contagion effects. Conversely, macroeconomic shocks, which affect many banks at once,

[1] Alternatively, additional network layers can connect banks through common exposures as in Montagna & Kok (2016) or shared information as in Ding et al. (2017).

have frequently triggered financial crises (viz., the Peso crisis of 1994, the Asian financial crisis of 1997 or the Ruble crisis of 1998).[2]

Moreover, researchers and policy makers (e.g., Georgieva 2020) have recently warned about the global dominance of the US dollar and the implications this has for economic and financial stability.[3] In particular emerging markets rely heavily on a stable exchange rate towards the dollar. The ongoing pandemic has only amplified the problem (see, e.g., Hofmann et al. 2020). Therefore, in our analysis, we will lay emphasis on the question of how asymmetries in the use of different currencies can amplify or dampen financial contagion effects. We do so by simulating stylized multicurrency interbank markets and studying how these markets behave when one of the currencies in the system suddenly gains or loses in value.[4]

Our paper makes two important contributions to the literature. First, we develop a framework for the study of financial contagion in which knock-on defaults are not triggered by an initial idiosyncratic bank failure but a currency crisis. Such exchange rate shocks have in the past been one of the most frequent sources of financial contagion.[5] Second, our paper derives important results regarding asymmetries in banks' exposures denominated in different currencies.

[2]Even though our approach is based on simulations, we would nonetheless like to point to the work of Gounopoulos et al. (2013) who study the relationship between financial contagion effects and exchange rate shocks empirically. Using the VAR-BEKK methodology with a structural break during the great financial crisis the authors show that banks' equity returns have responded negatively to exchange rates during this period of time lending support to the "flight to quality hypothesis". Of course, in an empirical setup, one would ideally like to identify exchange rate shocks separately from other macroeconomic shocks.

[3]At least since Gopinath et al. (2010) it has been known that pass-through effects of exchange rate changes are sensitive according to whether goods are invoiced in local currencies or US dollars.

[4]At the time of writing, the world finds itself in a state of severe economic turmoil due to the ongoing coronavirus pandemic. In the wake of this crisis, many exchange rates initially experienced dramatic increases in volatility with currencies gaining or losing up to 25 % in value in a matter of weeks (Collins & Gagnon 2020). IMF officials even fear that "it is very likely that this year the global economy will experience its worst recession since the Great Depression" (Gopinath 2020, p. v).

[5]Macroeconomic shocks have so far largely been ignored by the financial contagion literature. One of the very few exceptions is Elsinger et al. (2006) who consider macroeconomic shocks such as FX shocks and shocks to stock markets and interest rates.

A key result of our paper is that a strongly dominant currency, in which many banks borrow, can be a significant source of financial contagion.

The paper is organized as follows. Section 2 relates our work to the literature. Section 3 describes a framework of multicurrency interbank markets. Section 4 then uses this framework to conduct a series of Monte Carlo simulations of stylized interbank markets. Thereafter, Section 5 studies how these simulated multicurrency interbank markets behave, when one of their currencies suddenly appreciates or depreciates. Various subsections explore how changes to the different simulation parameters affect the ensuing contagion process. The same section also conducts a policy exercise. Section 6 concludes.

2 Related literature

One of the earliest branches of the systemic risk literature deals with the question of how idiosyncratic bank failures might cause subsequent defaults of other financial institutions. To this end, financial contagion has typically been modeled using a matrix of bilateral exposures. Such a matrix records how much banks stand to lose in case one of their debtors defaults. When an initial financial institution fails, its creditors might experience losses greater than their own capital reserves. Consequently, they will default, too. These second-round bank failures might then induce a third round of bank failures and so on. Eventually, the system reaches a new equilibrium in which no further bank defaults.

By applying the mechanics of an interbank market's exposure matrix to any possible initial default in this market, researchers can gauge how robust or fragile it is. Analyses of this kind have been carried out for many real-world interbank markets (e.g., Furfine (2003), Wells (2002), Upper & Worms (2004), Mistrulli (2011), Sheldon & Maurer (1998), Blåvarg & Nimander (2002), van Lelyveld & Liedorp (2006), Degryse & Nguyen (2007), Diez Canedo & Martínez

Jaramillo (2009), for the interbank markets of the US, the UK, Germany, Italy, Switzerland, Sweden, the Netherlands, Belgium and Mexico, respectively) as well as simulated interbank markets (see, e.g., Iori et al. 2006, Nier et al. 2007, Roukny et al. 2013, Leventides et al. 2019).

Financial exposure, of course, comes in many forms. As a result, a large branch of the literature has been devoted to the identification and measurement of financial contagion. Pericoli & Sbracia (2003), Dungey et al. (2005), and Rigobón (2019), survey the empirical evidence as well as the methodological challenges in detecting contagion in financial markets. Currency crises, often defined as a sharp depreciation or devaluation of a currency, alongside banking crises, are often treated as a primary source of contagion effects.

Another branch of the literature has explored various channels of financial contagion. Cifuentes et al. (2005), Gai & Kapadia (2010) and Ding et al. (2017) introduce asset prices into their models, such that banks propagate shocks not only via their immediate bilateral linkages but also via reduced asset prices. A similar route is taken by Greenwood et al. (2015), where banks are forced to sell assets to meet target levels of leverage. Müller (2006) and Gai et al. (2011) endogenize liquidity shortages. In their models, troubled banks stop extending credit to other banks and begin hoarding liquidity, which again inflicts losses at other banks. Fink et al. (2016) introduce a "credit quality" channel. Through this channel, shocks not only spread to other banks once a default has actually occurred. Instead, a shock spreads from a debtor bank to its creditors as soon as its default becomes more likely. Lee (2013) and Teply & Klinger (2019) propose models in which banks hold two types of assets: liquid assets and illiquid assets. When in trouble, banks must sell some of their more liquid assets to cover losses on their illiquid assets. Again, these fire-sales then induce losses at other banks.

Naturally, the notion of different contagion channels and the modeling of different types of assets provides a smooth transition towards the more modern understanding of interbank markets as multiplex networks. A number of papers have empirically analyzed the similarities, differences and relationships between the different layers of such networks (e.g., Langfield et al. 2014, Bargigli et al. 2014, Aldasoro & Alves 2018, for the interbank markets of the UK, Italy, and Europe as a whole, respectively). Poledna et al. (2015) show that modeling interbank markets as networks with multiple layers has important implications for assessing systemic risk. Using very granular data on Mexican banks, the authors distinguish between four layers of different exposures in the Mexican interbank market. In this multiplex network, banks are connected via deposits and loans, security holdings, derivatives, and uncleared FX transactions. The authors then demonstrate that systemic risk, when computed for the entire multiplex network, is greater than the sum of the same systemic risk scores evaluated at the network's individual layers.

Our own work is closely related to that of Montagna & Kok (2016) and Gabrieli & Salakhova (2019). Both study knock-on defaults using simulated interbank markets with multiple layers. Our work is also related to Elsinger et al. (2006) who have also studied macroeconomic shocks as sources of financial contagion, albeit in interbank markets with a single currency. As we shall remark again later, this extension poses challenges given the absence of data on exposures denominated by currency. That said, when seen through capital flows, there is country level evidence that banks in emerging markets especially suffer in proportion to their exposure to currencies other than their own (e.g., Park & Shin 2020). Indeed, there is a large broader literature that associates currency exposure, particularly in response to a depreciation or devaluation, with negative consequences for banking systems and the economy more widely. For example, Koutmos & Martin (2003) underscore both the importance of currency exposure as well as asymmetries in the impact of exchange rate shocks notable for the financial sector. The banking sector may well be more vulnerable because of financial frictions which will be partly a function of how concentrated the industry is (see, e.g., Dell'Ariccia 2001, Ordoñez 2013). Dominguez & Tesar (2006) also highlight the importance of currency exposure at the firm and industry levels in both industrial and emerging markets where it is found to be high.

Montagna & Kok (2016) simulate interbank markets with different maturities and correlated assets based on a probability map which they calibrate to match key characteristics of the European interbank market.[6] Gabrieli & Salakhova (2019) use a similar approach. But unlike Montagna & Kok (2016) they consider two types of initial shocks: Idiosyncratic bank failures and simultaneous equity shocks to all banks in the system. In what follows, we too simulate multiplex interbank markets. We also consider common shocks instead of idiosyncratic bank failures and we also model different maturities. Additionally, we add a fourth dimension to the interbank network to introduce different currencies into to the system. This enables us to study exchange rate shocks as triggers of cascading defaults, a source of contagion not yet explored in the manner done here in the current literature.

3 Multicurrency interbank markets

To describe multicurrency interbank markets with different maturities and different currencies, we follow Avdjiev et al. (2019) and generalize the traditional interbank lending matrix to a multidimensional interbank lending array or tensor. In our case this tensor is of dimensions $n_b \times n_b \times n_c \times n_m$, where n_b denotes the number of banks in the system, n_c the number of currencies and n_m the

[6]In the context of simulating interbank marekts, this concept has been pioneered by Hałaj & Kok (2013).

number of maturities. The tensor element $x_{i,j,k}^{(l)}$ resembles the amount of money that bank i is due to receive from bank j in currency k in period l.

To fully appreciate the multidimensional structure of this generalized interbank market, let us for a moment assume that all loans are denominated in the same currency and that all loans mature at the same time. In this case the market can be completely described by a classical interbank lending matrix. The individual elements of this matrix resemble the loans that banks grant each other. The ij^{th} element of this matrix describes the exposure of bank i towards bank j. As no bank lends to itself, the main diagonal of the interbank lending matrix is equal to zero. Once we introduce different currencies to the system, we need to generalize this two-dimensional matrix to a three-dimensional array. Figure 1 illustrates the resulting cuboid graphically. The cuboid consists of n_c different layers. Each slice is an $n_b \times n_b$ lending matrix that summarizes the interbank loans denominated in one of the n_c different currencies. As in the two-dimensional case, the main diagonal of each layer is equal to zero. Notice that without loss of generality, all of the array's n_c layers can be expressed in a single currency.

[Figure 1 about here.]

Once we introduce different maturities to the system, we have to generalize the three-dimensional array to a four-dimensional one.[7] This hyperrectangle now contains n_m different cuboids which each contain n_c interbank lending matrices of dimensions $n_b \times n_b$. Each of the n_m cuboids summarizes the flows of funds between banks for a different period. Positive cashflows resemble interbank assets while negative cashflows resemble interbank liabilities. In pe-

[7] In a previous draft we assumed infinite maturities. At the suggestion of a referee we relaxed this assumption by adding an additional dimension to the array in Figure 1. Earlier results are relegated to an appendix. Broadly, our principal conclusions are unaffected. However, gaps between the baseline and various scenarios can change for large currency appreciations for the most part. Losses often rise more quickly for smaller depreciations and appreciations than in the case when maturity differences are not permitted.

riod $t + l$, bank i will experience a positive cashflow, i.e., it has an interbank asset, of

$$A_i^{(l)} \equiv \sum_{j=1}^{n_b} \sum_{k=1}^{n_c} x_{i,j,k}^{(l)} \; . \tag{1}$$

Similarly, in the same period, a bank j has an interbank liability, or negative cashflow, of

$$L_j^{(l)} \equiv \sum_{i=1}^{n_b} \sum_{k=1}^{n_c} x_{i,j,k}^{(l)} \; . \tag{2}$$

When summing across maturities and borrowers, one can compute a bank i's exposure towards a given currency k as $\sum_{j=1}^{n_b} \sum_{l=1}^{n_m} x_{i,j,k}^{(l)}$.

In addition to their interbank assets and their interbank liabilities, banks also have nonbank assets A_i^{NB} and nonbank liabilities L_i^{NB}. Throughout we assume that these nonbank assets and nonbank liabilities do not reach their maturity, which is why they have no superscript (l). Lastly, banks hold a cash position C_i and have equity E_i. The balance sheet identity requires that

$$\sum_{l=1}^{n_m} A_i^{(l)} + A_i^{NB} + C_i \equiv \sum_{l=1}^{n_m} L_i + L_i^{NB} + E_i \; . \tag{3}$$

Table 1 illustrates the structure of banks' balance sheets graphically.

This generalization of traditional single-currency interbank markets enables us to model two sources of financial contagion. First, like traditional interbank markets with a single currency, multicurrency interbank markets can suffer from shocks to nonbank assets. If a particular bank cannot survive such a shock and defaults, all of this bank's interbank liabilities, which are the interbank assets of other banks, are erased from the interbank market, i.e., all of these array elements are set to zero. Second, multicurrency interbank markets can suffer from exchange rate shocks. In this case, one particular layer of the interbank lending array increases or decreases by a certain percentage. Both shock scenarios directly impact a bank's balance sheet. If any bank suffers a loss in its assets or an increase in its liabilities greater than its equity, this bank will default, too, and potentially trigger an entire default cascade. In what follows we focus on this second channel of contagion.

4 Monte Carlo simulations

The preceding section has described how traditional approaches to assessing contagion in single-currency interbank markets can be generalized to the case of multicurrency interbank markets. In the upcoming section, we describe how we simulate different interbank markets within this multicurrency framework. Thereafter, we submit these simulated multicurrency interbank markets to a series of stress-tests to study how prone they are to financial contagion effects triggered by exchange rate shocks. Note, however, that our framework is not limited to simulated interbank markets. Instead, one could readily use it to investigate real-world interbank markets, too.

4.1 Simulation parameters

Both the traditional interbank lending matrix and the multi-dimensional interbank lending array used here describe a network or graph. The nodes or vertices of this network are the different banks. The network's links or edges are the banks' bilateral exposures. As these exposures resemble credit relationships between a creditor bank and borrower bank, they are weighted and directed. In our simulation framework, each bank can borrow both in its home currency and in foreign currency across all maturities. We let l_i denote the number of banks from which bank i borrows in domestic currency. Analogously, l'_i denotes the number of banks from which bank i borrows in foreign currency. To ensure heterogeneity across banks, l_i and l'_i are realizations of two random variables that are uniformly distributed on the intervals $[0, l]$ and $[0, l']$, whereby l and l' are two exogenous parameters.[8] The resulting network will thus feature a uniform degree distribution. Moreover, links can run in opposite directions between the same two banks. This is consistent with typical bankruptcy regulations which do not allow the netting of individual positions.

A third parameter s is then used to control the size of banks' exposures. We model loan volumes such that banks vary significantly in terms of their so-called systemic importance. The Basel Committee on Banking Supervision (2018) determines the global systemic importance of banks based on the following criteria: cross-jurisdictional activity, size, interconnectedness, degree of substitutability, and complexity. As the latter two criteria are rather technical and refer to specific revenue-based figures and balance sheet items, we focus on the first three of these indicators. In our framework, banks' levels of cross-jurisdictional activity are governed by l', while their levels of overall interconnectedness are driven by both l and l'. To directly control the systemic importance of large banks in our simulation framework, we set each of bank i's exposures equal to $s_i = (l_i + l'_i)^s$, whereby s is again an exogenous simulation parameter. Because s enters this equation in the exponent, this procedure ensures that the loan volumes of well-connected banks are disproportionately larger the greater s. Thus, by adjusting s, we can alter the systemic importance of these banks.

Given banks' interbank assets and interbank liabilities, we then use two exogenously determined ratios r_1 and r_2 to determine their nonbank assets and nonbank liabilities. Multiplying each bank's interbank assets with r_1 yields banks' nonbank assets.[9] Similarly, banks' equity levels follow from multiplying

[8]Potential real world drivers of a bank's willingness to borrow from other banks are, e.g., forecasts of future economic growth. Depending on whether such forecasts pertain to the domestic market or foreign markets, this will either affect l or l'.

[9]In case a bank has a net liability position in the interbank market, we determine its nonbank assets by multiplying r_1 with its interbank liabilities. This procedure ensures that none of the balance sheet items becomes negative.

each bank's total assets with r_2. Next, we set each bank's cash position equal to the greater of its next-period cashflows. Lastly, banks' nonbank liabilities follow from the balance sheet identity in equation (3). The two parameters r_1 and r_2, thus, determine how heavily banks rely on interbank assets in relation to nonbank assets and how large their equity is.

In addition to the simulation parameters explained above, our simulation framework comprises two discrete probability distributions. A first distribution (D_1) controls the number of banks located in each currency area. A second discrete probability distribution (D_2) controls the preferences that banks, when borrowing in foreign currency, have vis-à-vis the different foreign currencies. In effect, these two probability distributions control how important the different currencies are in the global banking market. Note that a currency can be dominant because of two reasons: There are either many banks located in this currency area that borrow domestically or this currency is the favorite choice for borrowing in foreign currency.

4.2 Simulation procedure

Given a set of simulation parameters $n_b, n_c, n_m, l, l', s, r_1$ and r_2, and the distributions D_1 and D_2, our simulation procedure consists of the following steps:

1. Depending on D_1, randomly determine each bank's home currency.
2. Depending on l and l' as well as D_1 and D_2, randomly determine which of each bank's possible domestic and foreign lending relationships materialize.
3. Depending on the total number of each bank's liabilities, turn each bank's linkages into exposures based on the simulation parameter s.
4. Depending on the resulting interbank market and r_1, determine each bank's nonbank assets and cash position.
5. Given each bank's total amount of assets, use r_2 to determine each bank's equity level.

6. Nonbank liabilities follow from the balance sheet identity in equation (3).
7. Simulate the financial contagion effects of exchange rate shocks of varying magnitude.
8. Repeat steps 1-7 1000 times.

An example of a simulated interbank market is given in Appendix A.

4.3 Comparing simulated markets

To compare markets simulated from different parameter values, we compute three different metrics. The first of these measures is the "density" (D) of the interbank market. A network's density is defined as its share of non-zero edges. In our case, this is the number of non-zero interbank relationships, such that D is computed as

$$D = \frac{\sum_{x_{ijk}^{(l)} \neq 0} 1}{n_c \cdot n_m \cdot (n_b^2 - n_b)} \,. \tag{4}$$

Notice that higher or lower density does not automatically imply greater or lower financial contagion effects. While sparse interbank networks have fewer routes that default shocks can travel on, they typically also feature greater asymmetry in exposures. In this case, the failure of a single critical bank can cause the collapse of the entire market.

Therefore, we compute a second measure which is directly related to financial contagion. We refer to it as the "share of unilaterally critical linkages" (UCL). These are loans that exceed the creditor's equity. Consequently, a default on such a loan will automatically trigger the failure of the creditor bank:

$$UCL = \frac{\sum_{x_{ijk}^{(l)} > E_i} 1}{\sum_{x_{ijk}^{(l)} \neq 0} 1} \,. \tag{5}$$

UCL will be particularly high in sparse networks with large individual exposures relative to banks' total interbank exposures. In this case, large fractions of banks' exposures are concentrated on a relatively low number of linkages. The repayment of these loans is thus critical for the survival of the creditor banks. As argued by Craig & von Peter (2014), sparse interbank markets are empirically far more common than high-density interbank markets with relatively small individual exposures.[10] While D will, by design, be approximately the same for each of the 1000 realizations per set of parameters, UCL will vary more strongly. In each crisis simulation, we, therefore, compute the average value of UCL across the 1000 simulated markets.

Finally, we analyze banks' systemic importance. To this end, we compute a version of the "global systemic importance" index developed by the Basel Committee on Banking Supervision. The BCBS's original index consists of five equally weighted sub-indexes pertaining to the five criteria of systemic importance explained above. In our version of the index, we only use the first three of these criteria, i.e., cross-jurisdictional activity, bank size, and interconnectedness. A bank's level of cross-jurisdictional activity (CJA) is measured as the average amount of assets and liabilities it holds in foreign currency, i.e.,

$$CJA_i = 1/2 \cdot \left(\sum_{jkl:\, k \neq h_i} x_{ijk}^{(l)} + \sum_{ikl:\, k \neq h_i} x_{ijk}^{(l)} \right) , \tag{6}$$

where h_i denotes bank i's home currency.

Second, a bank's size (S) is computed as the sum of its interbank assets, nonbank assets and its cash position, i.e.,

$$S_i = \sum_{l=1}^{n_m} A_i^{(l)} + A_i^{NB} + C_i \ . \tag{7}$$

Lastly, a bank's interconnectedness (IC) is determined by the number of loans

[10]Nonetheless, it should be noted that financial contagion can also arise in situations where UCL is low. While less likely than when UCL is high, such scenarios can still occur if there are numerous creditors that are, e.g., dependent on the repayment of loans from any two separate borrowing banks.

it granted to and received from other banks.

A bank's global systemic importance (GSI) is then computed as an equally weighted average of each of these three subindexes relative to their respective market totals:

$$GSI_i = 1/3 \cdot \frac{CJA_i}{\sum_i CJA_i} + 1/3 \cdot \frac{S_i}{\sum_i S_i} + 1/3 \cdot \frac{IC_i}{\sum_i IC_i} \ . \tag{8}$$

By design, when summing across banks, GSI sums up to one or 100 %. Similar to UCL, banks' systemic importance will also vary across different simulations. Hence, we report the averages across the 1000 simulated markets.

5 Currency crisis simulations

In the preceding section we outlined our framework for simulating multicurrency interbank markets. In this section, we now simulate such markets with different sets of simulation parameters. For each set of parameters, we simulate 1000 interbank markets and study how these are affected by different exchange rate shocks. After explaining the default mechanism of our model, we begin with a baseline case and then alter the simulation parameters in various alternative scenarios. In our analysis, we focus on the loss of banks' nonbank liabilities. These liabilities are the deposits made by non-banking institutions. Losses on these liabilities are, therefore, the ultimate spillover from the banking sector to the real economy.

5.1 The contagion mechanism

In our model, banks have interbank assets and interbank liabilities that are denominated in different currencies and mature in different time periods. In each period banks receive a positive cashflow from their maturing assets and a negative cashflow from their maturing liabilities. At the end of each period t, banks need to maintain a sufficiently large cash position to cover their net cashflow in period $t+1$. In case a bank's interbank liabilities are greater than its interbank assets, the bank needs to roll over some of its debt by borrowing fresh money from other banks. It does so by selling new bonds that mature in period $t+2$. For other banks to provide fresh funds, we first require that the illiquid bank has non-negative equity. But even if the troubled bank has positive equity, other banks might still be reluctant to borrow, especially during an ongoing financial crisis in which banks find themselves in a scramble for cash. Therefore, we assume that a bank i, that has some cash to spare, extends loans to other banks only with probability

$$\pi(C_i, t) = e^{-t/C_i} , \tag{9}$$

where t is the number periods that have passed since the initial currency shock. This functional form implies that in the early stages of a crisis banks are still relatively likely to lend to each other. While this increase in financial market linkages will alleviate the stress that is put on some banks, it also increases the potential for severe financial spillovers later on, when equation (9) implies an ever smaller chance for banks to continue lending.

A crisis starts with an exchange rate shock of size x to currency y. This currency shock changes the value of interbank exposures denominated in this currency by x percent. In case of an appreciation of y, banks that are net borrowers (lenders) in currency y, will experience a loss (gain) in equity. After this initial shock, banks engage in interbank lending to fulfill their cash needs for the next period. In random order, all banks needing cash approach all potential lenders to ask for a loan to roll over their debt. Whether or not a potential lender extends a loan is determined by equation (9). If the lending bank has more money to spare than the debtor bank needs, we assume that the lending bank extends a loan in the home currency of the debtor that covers all of the debtor's cash needs. Debtors that are unable to raise enough cash to repay their now maturing interbank liabilities default together with all those banks whose equity had been wiped out by the initial currency shock.

The crisis now advances to the next period. Throughout, we follow Gai & Kapadia (2010) and Leventides et al. (2019), who also work with simulated interbank markets, and assume that creditor banks cannot make any recoveries from defaults on their loans. This means that any funds that other banks had supplied to the defaulters of the preceding round, both before and after the initial currency shock, are now lost. If these losses exceed the equity of some of the creditors, knock-on defaults set in and the crisis continues. The crisis stops once no further bank defaults.

5.2 Baseline simulation

In the baseline scenario, we simulate a market with $n_b = 100$ banks, $n_c = 4$ different currencies and $n_m = 10$ different maturities. We set $l = 100$ and $l' = 100$, such that on average each bank takes out 50 loans in domestic currency and 50 loans in foreign currency. We choose $s = 2$, such that loans taken out by the average bank are of size $(50 + 50)^2 = 10,000$. We assume, for now, that on average all currency areas are home to the same number of banks. As there are four different currencies, we set $D_1 = (0.25, 0.25, 0.25, 0.25)$. Moreover, we also assume that $D_2 = (0.25, 0.25, 0.25, 0.25)$. This means that when borrowing from abroad, banks have no particular preference over different currencies. Of course, both of these assumptions are very unrealistic. Later on, we vary these assumptions via a set of alternative calibrations. There, we will pay particular attention to the case where a large number of banks which are, e.g., located in emerging markets, have large liabilities in one particular currency, e.g., the US-dollar. Lastly, we set $r_1 = 1$ and $r_2 = 0.05$. This means that banks maintain an equity ratio of 5 % and have just as many interbank assets as nonbank assets. However, on average, banks' nonbank assets greatly surpass their short-term interbank assets.

As explained above, we use these specifications to simulate 1000 markets and study how each of them reacts to exchange rate shocks ranging between -50 % and +50 %.[11] Table 2 summarizes the markets' key characteristics, which have been discussed in Section 4.3. The density of the average baseline interbank network amounts to $(100 \cdot (50 + 50))/(4 \cdot 10 \cdot (100^2 - 100)) = 0.025$, suggesting that 2.5 % of all possible links in the network are realized. Around 7 % of these interbank loans are unilaterally critical, i.e., they are larger than the creditors' equity such that defaults on these loans will immediately cause subsequent bank failures. Lastly, the global systemic importance of the top five most important banks ranges between 1.8 and 2.1 percent.

[Table 2 about here.]

As we assume that all currency areas are home to the same number of banks and no currency is preferred over another when banks borrow in foreign currency, the same exchange rate shock will have the same effect for all different currencies. Thus, we only show the results for shocks to Currency 1. These are displayed in subfigure (a) of Figure 2. In this figure, the horizontal axis depicts the different exchange rate shock sizes, while the vertical axis shows the resulting losses in nonbank assets averaged across the 1000 simulated markets.

[Figure 2 about here.]

Obviously, the loss in assets is the greater the larger the initial currency shock and no losses occur if the shock size is equal to zero. Thus, for all cur-

[11] An oft-used definition of a currency crisis usually involves a depreciation of the nominal exchange rate that exceeds 25 % on an annual basis. See, for example, Frankel & Rose (1996). Hence, our chosen values comfortably exceed commonly used thresholds.

rencies, the results follow a U-shaped pattern around zero. When starting from zero and moving to the left, we observe that practically no losses occur up until a shock size of around -15 %. Thereafter, the losses quickly increase the greater the shock size. For depreciations greater than -20 % this effect starts to levels off, but on average shocks of this size already wipe out some 80 % of all liabilities to nonbanks. For depreciations greater than -30 % the entire banking system always collapses. For positive exchange rate shocks we also observe that no losses occur up until a shock size of around +15 %. Thereafter, however, the loss in interbank liabilities increases more quickly than in the case of negative shocks. Now, appreciations of about +20 % are enough to guarantee a complete failure of the banking system.

As explained before, banks can default because of two reasons. First, they suffer losses on their assets due to the initial exchange rate shock. Second, they suffer losses on some of their interbank assets due to the defaults of other banks. To better understand which of these reasons dominates, we calculate for each run of the simulation the share of defaulters that defaults in the first round of the simulation. Subfigure (b) of Figure 2 displays the distribution of these shares. As we can see, most defaults do not occur in the first round of the simulations. This suggests that banks typically collapse in later rounds, when defaults are driven by knock-on effects.

5.3 Greater nonbank assets and higher equity

We begin our analysis of alternative scenarios by increasing the parameters r_1 and r_2, i.e. the ratio of nonbank to interbank assets and the equity ratio. Naturally, higher levels of equity directly reduce the risk of financial contagion as banks have greater cushions to survive failing interbank loans. Similarly, a greater reliance on nonbank assets makes a bank less vulnerable to financial contagion in the interbank market. This holds for both single-currency and multicurrency interbank markets alike. However, as we model a multicurrency interbank market where banks are located in different currency areas, an exchange rate shock will not affect all banks in the same way. If a bank sees its home currency depreciate, all of its assets and liabilities lose in value. Its equity thus increases or decreases depending on the currencies in which most of its interbank assets and interbank liabilities are denominated. Conversely, a bank located in another currency area only sees parts of its interbank assets change in value. Therefore, we expect the equity ratio r_2 to have a greater effect on financial contagion than r_1.

[Figure 3 about here.]

Figure 3 shows the effects of increasing r_1 from 1 to 3/2 and raising r_2 from 5 % to 7.5 % while keeping all other parameters constant. Figure 3 (a) shows the effects of increasing r_1, while Figure 3 (b) shows the effects of increasing r_2. In both charts white bars refer to the effects of exchange rate shocks in the baseline scenario, while red bars reflect the effects of exchange rate shocks in the new alternative scenarios. We observe that in both subfigures the red bars are shorter than the white bars, suggesting that the losses of interbank assets are, as expected, less severe than in the baseline scenario. This is unsurprising, as the increases in r_1 and r_2 significantly reduce the shares of unilaterally critical linkages in the market. These drop from around 7 percent in the baseline scenario to only 1.4 and 0.2 percent, respectively. At the same time, the increases in r_1 and r_2 have little to no effect on network density and the systemic importance of the largest banks in the market (see Table 2).

5.4 Greater network density and greater interbank exposures

Next, we investigate how the maximum number of loans denominated in domestic currency l and the maximum number of loans denominated in foreign currency l' affect financial contagion. Essentially, these two parameters determine the density of the interbank network. The effect of increasing network density on financial contagion is twofold. On the one hand, it increases the number of routes that shocks can travel on, such that shocks can now quickly affect many other banks before the default wave comes to a halt. This effect is particularly strong in extremely sparse networks. In fact, if the interbank market is so sparse that certain banks have no relation to other banks at all, not even through intermediary banks, their default can never affect these other banks. In this case, increasing the number of loans will merge these independent interbank markets into one large network of loans, such that financial contagion can now, at least in theory, affect all banks. On the other hand, once the interbank market has surpassed a critical level of interconnectedness, further increasing the density of the interbank market will help to spread banks' exposures more evenly across different counterparties. Banks are then less exposed to individual borrowers such that default waves are less likely to arise in the first place.

This twofold effect of network density arises in single-currency and multicurrency interbank markets alike. In addition to this, multicurrency interbank markets are also driven by the proportions of each bank's exposure denominated in domestic currency to its exposure denominated in foreign currency. If banks have increased interbank liabilities in domestic currency, they will be more robust towards depreciations of their home currency. Of course, banks located in other currency areas, who are the creditors to these interbank liabilities, will be more exposed to depreciations of this particular currency. However, depending on the number of currencies in the market, this increased risk is shared among many different banks, such that the overall risk of financial contagion decreases. Conversely, an increasing number of loans in foreign currency decreases financial robustness in the case of sudden depreciations.

[Figure 4 about here.]

Figure 4 shows the effects of altering l and l'. First, we increase the number of loans in domestic currency from $l = 100$ to $l = 200$. Thus, on average, banks now borrow money from one hundred instead of only fifty other banks in domestic currency. Table 2 shows that this change increases the average network density to around four percent. At the same time UCL decreases from around 7 % to only than 1.5 %. The effect this change has on the severity of exchange-rate-triggered banking crises is depicted in Figure 4 (a). Again, white bars refer to the baseline scenario, while red bars refer to the alternative. The results show that the effects of negative exchange rate shocks are now less pronounced than in the baseline scenario. Figure 4 (b) shows the results of increasing l' from $l' = 100$ to $l' = 200$. Here, positive exchange rate shocks have a smaller impact, but only slightly. Depreciations, however, now lead to greater losses than in the base line scenario. Lastly, we increase both l and l' from 100 to 200. Here, the interbank market's density amounts to 5 % on average, while the average share of unilaterally critical linkages plummets to less than one percent. The effects of this joint increase in the number of domestic and foreign loans are depicted in Figure 4 (c). Here, the effects of increasing l and l' largely seem to cancel out. Nonetheless, the losses due to sudden depreciations are still slightly less pronounced than in the baseline scenario.

Of course, the effects of different parameter values on financial contagion can be non-linear and even non-monotonic.[12] Given their twofold effect on financial contagion, this concern is particularly pressing for the parameters l

[12]See, e.g., the simulated interbank markets of Nier et al. (2007).

and l'. Therefore, we repeat the earlier analysis for a whole range of values for these two parameters. In particular, we study values of l and l' between 50 and close to 1000. The results of these exercises are displayed in Figure 10 in the appendix.

The results show that adding to the number of domestic loans significantly reduces the financial contagion effects of negative exchange rate shocks. This effect is particularly strong when $l < 400$. For values of l between 400 and 600 this effect is still there but becomes smaller, while increases of l beyond $l = 600$ have practically no effect on financial contagion. A completely different pattern emerges for increases in l'. First, i.e., when l' is very low, increases in l' worsen the impacts of negative exchange rate shocks. Once l' reaches a level of around $l' = 500$, further increases have once again no impact on financial contagion. Regarding joint increases of both l and l' we observe that the two effects described before seem to cancel out each other. Thus, on the whole, greater financial connectedness on home markets appears to reduce financial contagion effects, whereas greater connectedness to foreign markets appears to increase it. However, both of these effects only pertain to sudden depreciations. Losses due to positive exchange rate shocks are largely unaffected by the levels of l and l'.

Next, we consider changes to the parameter s. Recall that s controls the size of loans but also banks' so-called global systemic importance. In the baseline-scenario we set this value to $s = 2$. Now, we increase it to $s = 4$. Obviously, this change has no effect on network density. However, as can be seen from Table 2, it dramatically increases the share of unilaterally critical linkages and the systemic importance of the most important banks. Initially, around to 7 percent of all loans were critical to the survival of creditor banks. Now, this value increases to around 50 percent. Similarly, the global systemic importance of the top five banks ranged between 1.8 to 2.1 percent. Now, these banks' systemic importance ranges between 2.1 to 3.1 percent. The effects these changes have on financial contagion are displayed in Figure 5. Here, we see that shocks now have more pronounced effects than in the baseline scenario.

[Figure 5 about here.]

5.5 Alternative currency distributions

Now, we turn to one of the most important questions regarding the connection between financial contagion and exchange rates. This is the question of whether and how financial conditions are affected by the relative dominance of one or a few reserve currencies. To this end, we now vary the two distributions D_1 and D_2. While D_1 controls how many banks are located in one currency area, D_2 controls which currencies banks use when borrowing from abroad. We first change D_1 from $(0.25, 0.25, 0.25, 0.25)$ to $(0.8, 0.067, 0.067, 0.067)$. Then we do the same for D_2. In both cases there will be a clearly dominant currency and three equally small minor currencies. In the first case the asymmetry arises from banks' locations. In the second case the dominance of Currency 1 is due to banks' preference for using this particular currency when borrowing from abroad.

Figure 6 (a) shows the effects of exchange rate shocks to Currency 1 in the case of locational asymmetry. Figure 6 (b) does so for shocks to one of the minor currencies. The results show that positive exchange rate shocks to the major currency now have a smaller impact on financial contagion. Conversely, depreciations now trigger greater losses in interbank assets. A different pattern emerges for the minor currencies. Here, both appreceiations and depreciations now show smaller financial contagion effects and smaller losses than in the baseline scenario.

[Figure 6 about here.]

Finally, Figures 7 (a) and (b) repeat the analysis for asymmetry in foreign borrowing instead of asymmetry in bank location. Concerning exchange rate shocks to the relatively less dominant currencies, the results show that appreciations lead to greater losses than in the baseline scenario. Conversely, for the dominant currency, it is sudden depreciations that now trigger greater losses.

[Figure 7 about here.]

5.6 Policy intervention

The previous sections illustrate how the results of our simulations react to changes in key simulation parameters. The results show that greater nonbank assets, higher equity levels and greater interbank network density can significantly reduce financial contagion effects. Apart from the equity ratio, however, policy makers cannot directly alter these market characteristics. Nonetheless, policy makers can resort to different tools to mitigate financial contagion effects triggered by exchange rate shocks. In what follows, we analyze the effects of bank breakups. Similar policy exercises have, e.g., been carried out by Greenwood et al. (2015) or Ramadiah et al. (2020).

When splitting a bank in two, the easiest approach would be to split every asset and liability in half. One half would remain in the old bank, the other half would form a new bank. This procedure, however, would not reduce financial contagion. Both banks would be exposed to the exact same loans. In the event of a defaulting borrower, they would simultaneously fail and propagate the initial default shock to other banks just like the original bank would have done before the breakup. Therefore, we assume that policy makers attempt to create two roughly equally-sized smaller banks without splitting up individual exposures. This procedure ensures that the two smaller banks are not exposed to the same risks in the interbank market. Moreover, they have no loans between them. The failure of a third bank, which would have caused the original large bank to fail, will now only cause the failure of one of the two newly created smaller banks. Consequently, the default wave will now not immediately spread to all of the original bank's creditors. Intuitively, bank breakups, therefore, significantly reduce financial contagion. However, there is a second channel through which bank breakups affect financial contagion. The smaller banks will now have some loans on their balance sheets, whose failure the original large bank would have survived, but the smaller banks could not. This second channel works in the opposite direction of the first channel creating an ambiguous total effect.

[Figure 8 about here.]

Figure 8 shows the effects of exchange rate shocks in a scenario where, in terms of interbank liabilities, the top ten largest banks are broken up. We observe, that this policy intervention clearly fails to significantly reduce financial contagion effects. Regardless of whether exchange rate shocks are positive or negative, the loss in interbank assets is largely unchanged or even larger than in the baseline scenario.

6 Conclusions

This paper has developed a framework for studying financial contagion triggered by exchange rate shocks. To this end, we adapted the existing concept of multiplex interbank markets and simulated interbank markets with multiple currencies. Our results have shown that the contagion effects of exchange rate shocks are reduced if banks are well linked to other banks in their domestic currency. Increased exposures in foreign currency, however, have increased the potential for cascading defaults in response to sudden depreciations. Moreover, asymmetric currency distributions in the interbank market have also proven to increase systemic risk concerning negative exchange rate shocks. Lastly, the results of a policy exercises show that bank breakups need not lead to smaller systemic risk. To the contrary, bank breakups can increase the likelihood of knock-on defaults.

There are ample opportunities to extend our research. As stylized assumptions were necessary for tractability, and to retain the exclusive focus on exchange rate shocks, a critical extension of our paper would be an application of our concept of multicurrency interbank markets to real world data. Of course, a major obstacle for this kind of research would be the lack of data on bilateral exposures denominated in different currencies. A promising solution to this problem could be the use of calibrated probability maps à la Hałaj & Kok (2013), which have, in the context of multiplex interbank markets, e.g., been used by Montagna & Kok (2016) and Gabrieli & Salakhova (2019).

Another important avenue could be the introduction of additional channels of contagion. In this case, one would have to add further layers to the interbank network pertaining, e.g., to different asset classes. Algebraically, this would be no different than moving from the traditional two-dimensional exposure matrix to the three-dimensional and then four-dimensional exposure array used in this study. In addition to alternative contagion channels, researchers could also explore the role played by country-specific vs. global factors as drivers of contagion. The latter are undoubtedly important (e.g., see Dungey & Martin 2007) though possibly more relevant in some parts of the world than in others (e.g., also see Fratzscher 2003). For example, these factors could be explored by enriching a model like ours with additional economic variables. Future research could also focus on establishing some measure of the likelihood of a breakout of systemic crises triggered by currency shocks. For example, based on the historic frequencies and magnitudes of different exchange rate shocks, one could estimate the probability of financial crises of different magnitudes.

Another extension could also explore different types of policy interventions such as different varieties of bank taxes, e.g., so-called "financial stability contributions" as proposed by the IMF (2010). A classical example is the introduction of a common equity pool among all banks. These funds could then be used to avert the collapse of banks faced with bankruptcy. The equity pool would thus allocate equity to those parts of the financial system that need it the most. Consequently, financial crises could be stopped in their early stages when only a small number of banks are affected. Another type of policy has been proposed by Poledna & Thurner (2016). The authors study the effectiveness of a Pigovian tax on financial transactions aimed at internalizing the social costs of increased systemic risk caused by financial transactions. These types of policies could also be introduced to limit the amount of systemic risk due to foreign exchange exposures.

With a focus on simulated interbank networks, researchers could explore the implications of different degree distributions in multicurrency interbank networks. In this paper, we employed a uniform distribution. Alternatives to this approach are random interbank networks as in Nier et al. (2007) or entire sets of different degree distributions as in Gai & Kapadia (2010). Yet another way we could extend our research is to model situations where banks, in the event of mass-spread financial contagion, flee to or from a particular currency, even if the original shock did not affect that currency. This kind of modeling would allow for endogenous responses in the FX market. Then, instead of hoarding liquidity (see, e.g., Gai et al. 2011, Gabrieli & Salakhova 2019), banks would start hoarding currency. Lastly, an additional extension of our simulation model would introduce different constraints on banks located in different currency areas. For example, one could assume that banks located in emerging markets can only borrow in hard currency. This would allow for modeling in particular those exchange rate-triggered financial crises that are empirically most common, namely crises in emerging markets such as the Asian financial crisis.

There are also potential policy implications from our analysis. As Maggiori et al. (2019) point out, for the case of debt securities, currency denomination is an important component that shapes portfolios. If, as we suspect, this spills over into the banking system (via bonds held as assets), exchange rate shocks are also critical. Hence, concerns about the ability of stress-tests as an early warning system might want to pay more attention to the role of exchange rate shocks and the resulting contagion effects. The ongoing pandemic's impact on the volatility of exchange rates only serves to further highlight this concern despite the broadening of central bank swap lines, though these have clearly helped (Collins & Gagnon 2020). Moreover, since the dominance of the US dollar in debt markets is unlikely to be reversed anytime soon, this also means that the potential for contagion effects from large exchange rate shocks remains undiminished. Despite progress made by emerging markets in recent years to reduce their propensity to be exposed to the 'original sin' of borrowing in foreign currencies (Eichengreen & Hausmann 1999), risks still remain because investors have increasingly left themselves open to exchange rate risks (Carstens & Shin 2019).

References

Aldasoro, I. & Alves, I. (2018), 'Multiplex interbank networks and systemic importance: An application to European data', *Journal of Financial Stability* **35**, 17–37.

Avdjiev, S., Giudici, P. & Spelta, A. (2019), 'Measuring contagion risk in international banking', *Journal of Financial Stability* **42**, 36–51.

Bargigli, L., di Iasio, G., Infante, L., Lillo, F. & Pierobon, F. (2014), 'The multiplex structure of interbank networks', *Quantitative Finance* **15**(4), 673–691.

Basel Committee on Banking Supervision (2018), 'Global systemically important banks: Revised assessment methodology and the higher loss absorbency requirement', (July 2018).

Blåvarg, M. & Nimander, P. (2002), 'Inter-bank exposures and systemic risk', *Sveriges Riksbank Economic Review* (2), 19–45.

Carstens, A. & Shin, H. S. (2019), 'Emerging markets aren't out of the woods yet', *Foreign Affairs* . https://www.foreignaffairs.com/articles/2019-03-15/emerging-markets-arent-out-woods-yet.

Cifuentes, R., Shin, H. S. & Ferrucci, G. (2005), 'Liquidity risk and contagion', *Journal of the European Economic Association* **3**(2–3), 556–566.

Collins, C. G. & Gagnon, J. E. (2020), 'Exchange rate policy in the covid-19 pandemic', *PIIE COVID-19 series* . https://www.piie.com/blogs/realtime-economic-issues-watch/exchange-rate-policy-covid-19-pandemic.

Craig, B. & von Peter, G. (2014), 'Interbank tiering and money center banks', *Journal of Financial Intermediation* **23**(3), 322–347.

Degryse, H. & Nguyen, G. (2007), 'Interbank exposures: An empirical examiniation of contagion risk in the Belgian banking system', *International Journal of Central Banking* **3**(2), 123–171.

Dell'Ariccia, G. (2001), 'Asymmetric information and the structure of the banking industry', *European Economic Review* **45**(10), 1957–1980.

Diez Canedo, J. M. & Martínez Jaramillo, S. (2009), 'A network model of systemic risk: stress testing the banking system', *Intelligent Systems in Accounting, Finance & Management* **16**(1-2), 87–110.

Ding, D., Han, L. & Yin, L. (2017), 'Systemic risk and dynamics of contagion: a duplex inter-bank network', *Quantitative Finance* **17**(9), 1435–1445.

Dominguez, K. M. & Tesar, L. L. (2006), 'Exchange rate exposure', *Journal of International Economics* **68**(1), 188–218.

Dungey, M., Fry, R., González-Hermosillo, B. & Martin, V. L. (2005), 'Empirical modelling of contagion: a review of methodologies', *Quantitative Finance* **5**(1), 9–24.

Dungey, M. & Martin, V. L. (2007), 'Unravelling financial market linkages during crises', *Journal of Applied Econometrics* **22**(1), 89–119.

Eichengreen, B. J. & Hausmann, R. (1999), 'Exchange rates and financial fragility', *Proceedings from the Federal Reserve Bank of Kansas City Economic Policy Symposium* pp. 329–368.

Elsinger, H., Lehar, A. & Summer, M. (2006), 'Risk assessment for banking systems', *Management Science* **52**(9), 1301–1314.

Fink, K., Krüger, U., Meller, B. & Wong, L.-H. (2016), 'The credit quality channel: Modeling contagion in the interbank market', *Journal of Financial Stability* **25**, 83–97.

Frankel, J. A. & Rose, A. K. (1996), 'Currency crashes in emerging markets: An empirical treatment', *Journal of International Economics* **41**(3-4), 351–366.

Fratzscher, M. (2003), 'On currency crises and contagion', *International Journal of Finance & Economics* **8**(2), 109–129.

Furfine, C. H. (2003), 'Interbank exposures: Quantifying the risk of contagion', *Journal of Money, Credit, and Banking* **35**(1), 111–127.

Gabrieli, S. & Salakhova, D. (2019), 'Cross-border interbank contagion in the european banking sector', *International Economics* **157**, 33–54.

Gai, P., Haldane, A. & Kapadia, S. (2011), 'Complexity, concentration and contagion', *Journal of Monetary Economics* **58**(5), 453–470.

Gai, P. & Kapadia, S. (2010), 'Contagion in financial networks', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **466**(2120), 2401–2423.

Georgieva, K. (2020), 'IMF chief: we are rethinking our advice to emering markets', *Financial Times* .

Gopinath, G. (2020), Foreword to World Economic Outlook 2020: The Great Lockdown, International Monetary Fund, pp. v–vi.

Gopinath, G., Itskhoki, O. & Rigobon, R. (2010), 'Currency choice and exchange rate pass-through', *American Economic Review* **100**(1), 304–336.

Gounopoulos, D., Molyneux, P., Staikouras, S. K., Wilson, J. O. & Zhao, G. (2013), 'Exchange rate risk and the equity performance of financial intermediaries', *International Review of Financial Analysis* **29**, 271–282.

Greenwood, R., Landier, A. & Thesmar, D. (2015), 'Vulnerable banks', *Journal of Financial Economics* **115**(3), 471–485.

Hałaj, G. & Kok, C. (2013), 'Assessing interbank contagion using simulated networks', *Computational Management Science* **10**(2-3), 157–186.

Hofmann, B., Shim, I. & Shin, H. S. (2020), 'Emerging market economy exchange rates and local currency bond markets amid the covid-19 pandemic', *BIS Bulletin* (5), 1–7.

International Monetary Fund (2010), 'A fair and substantial contribution by the financial sector', pp. 1–74.
URL: *https://www.imf.org/external/np/g20/pdf/062710b.pdf*

Iori, G., Jafarey, S. & Padilla, F. G. (2006), 'Systemic risk on the interbank market', *Journal of Economic Behavior & Organization* **61**(4), 525–542.

Koutmos, G. & Martin, A. D. (2003), 'Asymmetric exchange rate exposure: Theory and evidence', *Journal of International Money and Finance* **22**(3), 365–383.

Langfield, S., Liu, Z. & Ota, T. (2014), 'Mapping the UK interbank system', *Journal of Banking & Finance* **45**, 288–303.

Lee, S. H. (2013), 'Systemic liquidity shortages and interbank network structures', *Journal of Financial Stability* **9**(1), 1–12.

Leventides, J., Loukaki, K. & Papavassiliou, V. G. (2019), 'Simulating financial contagion dynamics in random interbank networks', *Journal of Economic Behavior & Organization* **158**, 500–525.

Maggiori, M., Neiman, B. & Schreger, J. (2019), 'International currencies and capital allocation', *NBER Working Papers* (No. 24673).

Mistrulli, P. E. (2011), 'Assessing financial contagion in the interbank market: Maximum entropy versus observed interbank lending patterns', *Journal of Banking & Finance* **35**(5), 1114–1127.

Montagna, M. & Kok, C. (2016), ‘Multi-layered interbank model for assessing systemic risk’, *ECB Working Paper* (August).

Müller, J. (2006), ‘Interbank credit lines as a channel of contagion’, *Journal of Financial Services Research* **29**(1), 37–60.

Nier, E., Yang, J., Yorulmazer, T. & Alentorn, A. (2007), ‘Network models and financial stability’, *Journal of Economic Dynamics and Control* **31**(6), 2033–2060.

Ordoñez, G. (2013), ‘The asymmetric effects of financial frictions’, *Journal of Political Economy* **121**(5), 844–895.

Park, C.-Y. & Shin, K. (2020), ‘Contagion through national and regional exposures to foreign banks during the global financial crisis’, *Journal of Financial Stability* **46**, 100721.

Pericoli, M. & Sbracia, M. (2003), ‘A primer on financial contagion’, *Journal of Economic Surveys* **17**(4), 571–608.

Poledna, S., Molina-Borboa, J. L., Martínez-Jaramillo, S., van der Leij, M. & Thurner, S. (2015), ‘The multi-layer network nature of systemic risk and its implications for the costs of financial crises’, *Journal of Financial Stability* **20**, 70–81.

Poledna, S. & Thurner, S. (2016), ‘Elimination of systemic risk in financial networks by means of a systemic risk transaction tax’, *Quantitative Finance* **16**(10), 1599–1613.

Ramadiah, A., Caccioli, F. & Fricke, D. (2020), ‘Reconstructing and stress testing credit networks’, *Journal of Economic Dynamics and Control* **111**, 103817.

Rigobón, R. (2019), ‘Contagion, spillover, and interdependence’, *Economía* **19**(2), 69–99.

Roukny, T., Bersini, H., Pirotte, H., Caldarelli, G. & Battiston, S. (2013), 'Default cascades in complex networks: Topology and systemic risk', *Scientific Reports* **3**(1), 1–8.

Sheldon, G. & Maurer, M. (1998), 'Interbank lending and systemic risk: An empirical analysis for switzerland', *Swiss Journal of Economics and Statistics* **134**(4.2), 685–704.

Teply, P. & Klinger, T. (2019), 'Agent-based modeling of systemic risk in the European banking sector', *Journal of Economic Interaction and Coordination* **14**(4), 811–833.

Upper, C. (2011), 'Simulation methods to assess the danger of contagion in interbank markets', *Journal of Financial Stability* **7**(3), 111–125.

Upper, C. & Worms, A. (2004), 'Estimating bilateral exposures in the german interbank market: Is there a danger of contagion?', *European Economic Review* **48**(4), 827–849.

van Lelyveld, I. & Liedorp, F. (2006), 'Interbank contagion in the Dutch banking sector: A sensitivity analysis', *International Journal of Central Banking* **2**(2), 99–133.

Wells, S. (2002), 'UK interbank exposures: Systemic risk implications', *Bank of England Financial Stability Review* (December), 175–182.

A Example of a multicurrency interbank market

For illustrative purposes, we use our framework to simulate an interbank market with $n_b = 20$ different banks, $n_c = 3$ different currencies and $n_m = 2$ different maturities. Thus, in total, this market consists of $3 \cdot 2 = 6$ layers. These subnetworks each share the same set of nodes, which are the twenty different banks participating in the market. The edges of the subnetworks, i.e., the loans between the banks, will vary across the market's different currencies and maturities. The parameters l, l' and s are set to 5, 2 and 2, respectively. The currency distributions D_1 and D_2 are both equal to (0.65, 0.25, 0.1). Thus, most banks are expected to be located in the first currency area, while the fewest number of banks are expected to be in the third.

[Figure 9 about here.]

Figure (9) visualizes one of the many possible realizations that can be obtained when simulating an interbank market from these parameters. Each subfigure correpsonds to a different currency-maturity-combination. Subfigures (a) through (c) show the three subnetworks of loans maturing in period $t + 1$. Subfigures (d) through (f) show the three subnetworks of loans maturing in period $t + 2$. Nodes are colored differently, depending on the home currencies of the underlying banks: Grey for Currency 1, blue for Currency 2 and red for Currency 3. Edges are colored analogously depending on the currencies in which loans are denominated in. Edges always point from creditor to debtor bank. Loans maturing in period $t + 1$ are depicted using solid lines, loans maturing period $t+2$ are depicted using dashed lines. Subfigure (g) shows a combination of the first three subnetwors, i.e., all loans maturing in period $t+1$ regardless of their currency. Subfigure (h) does the same for loans maturing in period $t + 2$. Lastly, Subfigure (i) shows the complete network, i.e., all edges regardless of currency and maturity.

As expected, Currency 1 is the most dominant currency both in terms of the number of loans denominated in this currency but also the number of banks that have this currency as their home currency. Conversely, Currency 3, depicted in red, is the least dominant currency.

B Simulations across different parameter values

[Figure 10 about here.]

C Simulations with infinite maturities

This appendix shows the results of an earlier version of this paper which assumed infinite maturities. In this earlier model banks have no cash position. Neither do they extend any loans to each other during a currency crisis. Banks default once they have negative equity.

[Figure 11 about here.]

[Figure 12 about here.]

[Figure 13 about here.]

[Figure 14 about here.]

[Figure 15 about here.]

[Figure 16 about here.]

[Figure 17 about here.]

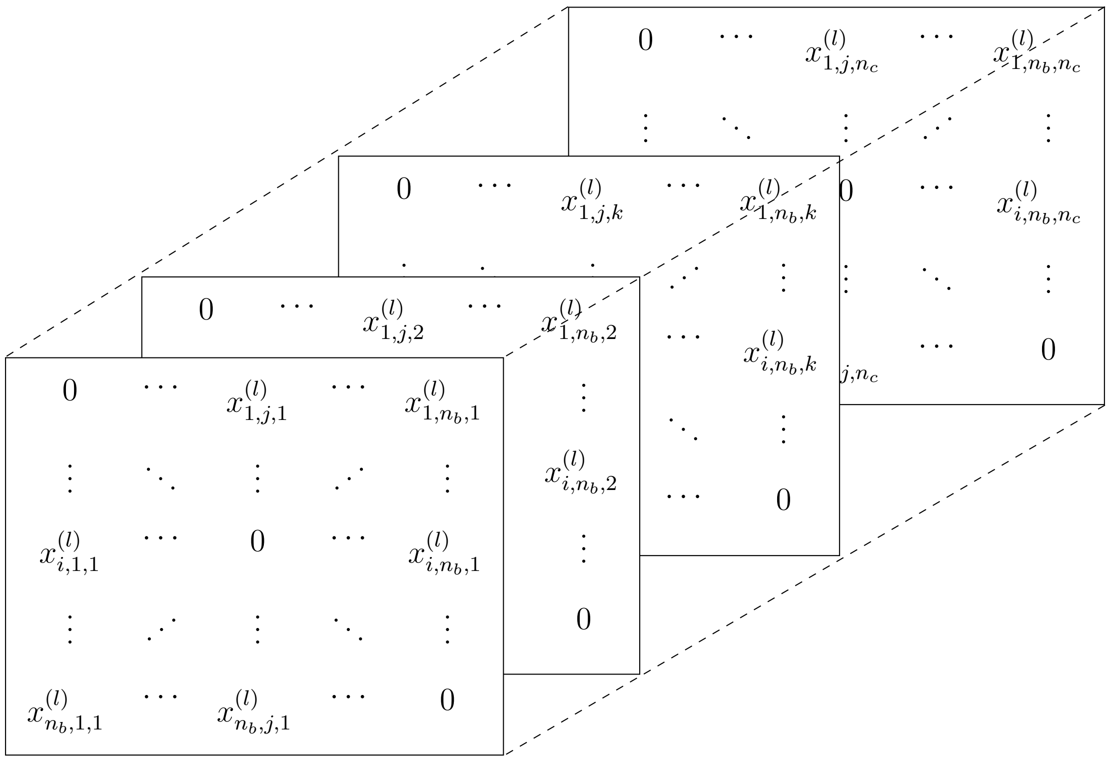


Figure 1: Interbank lending array

Note: The figure illustrates the interbank lending array of loans maturing in period $t + l$. Each of the n_c different slices corresponds to loans in a different currency. Within in each layer, row i (column j) resembles the interbank assets (liabilities) of bank i (j) in currency k. The main diagonals are equal to zero, as no bank lends to itself.

Table 1: Balance sheet of bank i

Assets		Liabilities	
Interbank assets	$A_i^{(1)}$	Interbank liabilities	$L_i^{(1)}$
	$A_i^{(2)}$		$L_i^{(2)}$
	$\vdots$		$\vdots$
	$A_i^{(n_m)}$		$L_i^{(n_m)}$
Nonbank assets	A_i^{NB}	Nonbank liabilities	L_i^{NB}
Cash	C_i	Equity	E_i

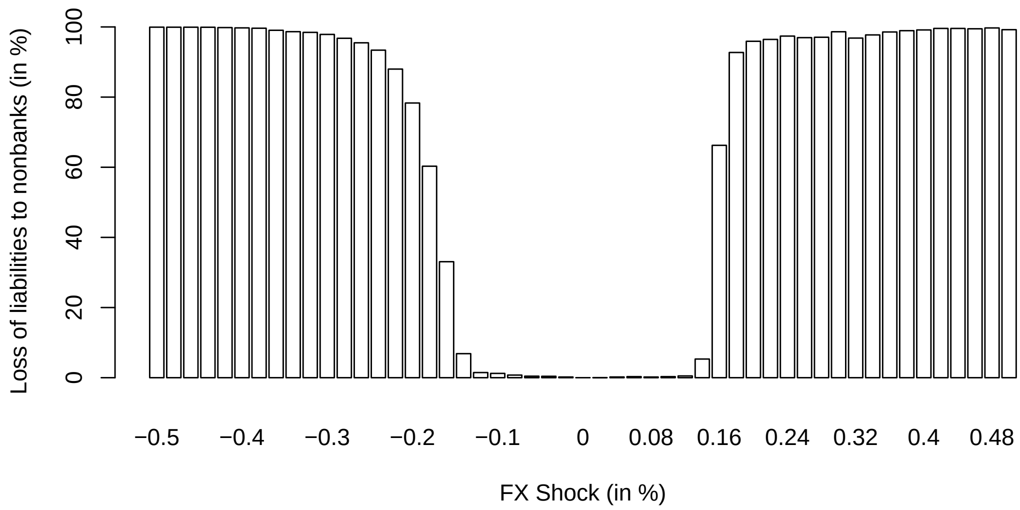
Note: This table illustrates the structure of banks i's balance sheet. The interbank positions $A_i^{(l)}$ and $L_i^{(l)}$ are defined in equations (1) and (2).

Table 2: Market characteristics in different scenarios

Scenario	Change to baseline	D (in %)	UCL (in %)	GSI_5 (in %)	GSI_1 (in %)
Baseline	-	2.5	7.3	2.1	1.8
Greater nonbank assets	$r_1 = 3/2$	2.5	**1.4**	2.2	1.8
Greater equity	$r_2 = 7.5\,\%$	2.5	**0.2**	2.1	1.7
More domestic loans	$l = 200$	**3.8**	**1.5**	2.2	1.8
More foreign loans	$l' = 200$	**3.8**	**2.1**	2.1	1.7
More loans overall	$l = 200,\ l' = 200$	**5.0**	**0.8**	2.1	1.7
Greater loan sizes	$s = 4$	2.5	**52.8**	**3.1**	**2.1**
Dom. in bank location	$D_1 = (0.8, 0.067, 0.067, 0.067)$	2.5	7.6	2.2	1.8
Dom. currency preference	$D_2 = (0.8, 0.067, 0.067, 0.067)$	2.5	6.7	2.1	1.8
Bank breakups	Breakup of ten largest banks	**2.1**	**1.3**	**1.6**	**1.4**

Note: The table summarizes which parameters have been changed in the different scenarios relative to the baseline scenario and how these changes affect the key characteristics of the simulated interbank market. D refers to the market's density, while UCL to the market's share of unilaterally critical linkages. GSI_5 denotes the systemic importance of the fifth most important bank. GSI_1 refers to the systemic importance of the bank with the greatest systemic importance. For each scenario, the reported values are the mean values across all 1000 simulated markets. The most important differences to the baseline scenario are typeset in bold.

(a) Simulation results



(b) First-round defaults

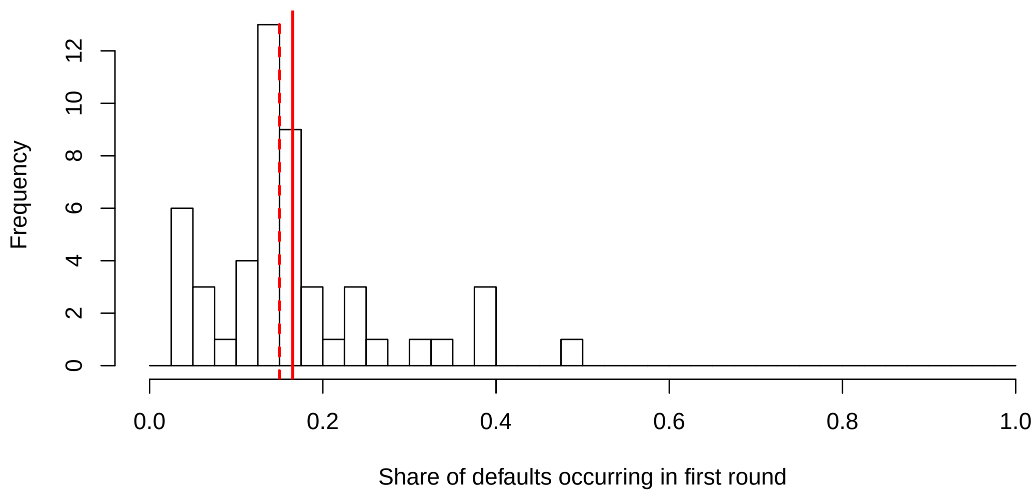
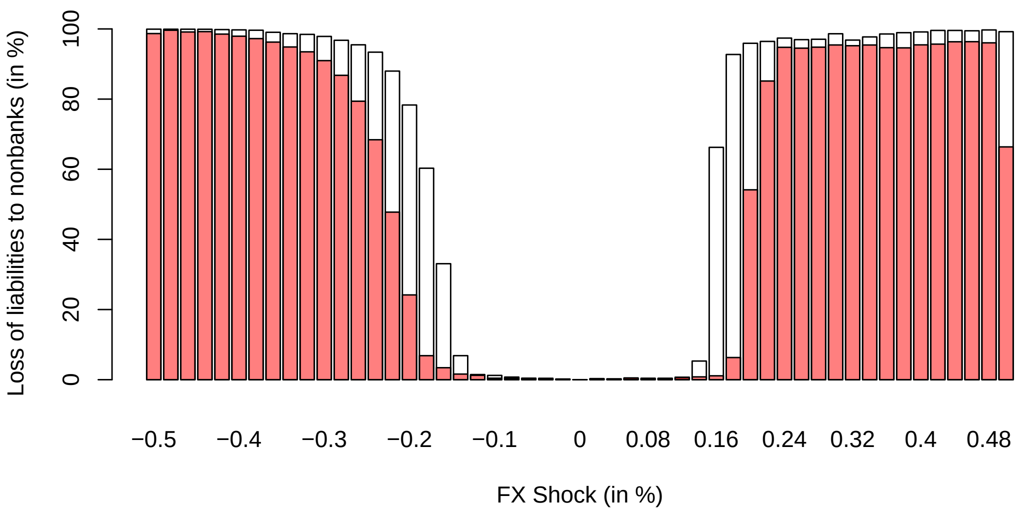


Figure 2: Baseline simulations

Note: Subfigure (a) depicts the losses in interbank liabilities that result in the baseline scenario. Subfigure (b) shows the distribution of the average share of first-round defaults. The solid (dashed) red line shows the mean (median) value.

(a) Greater nonbank assets



(b) Higher equity

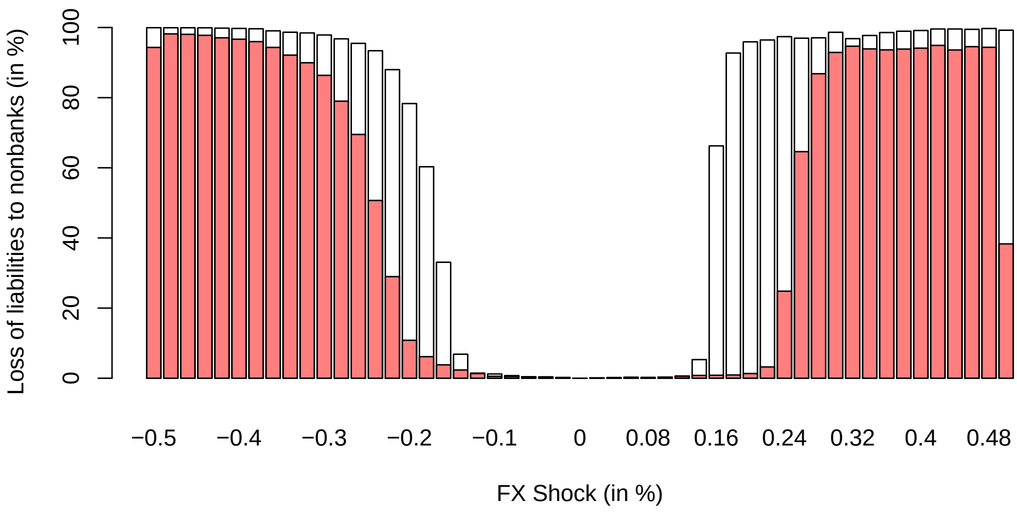
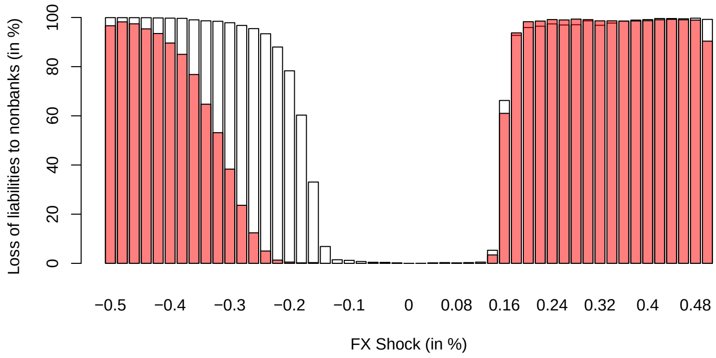


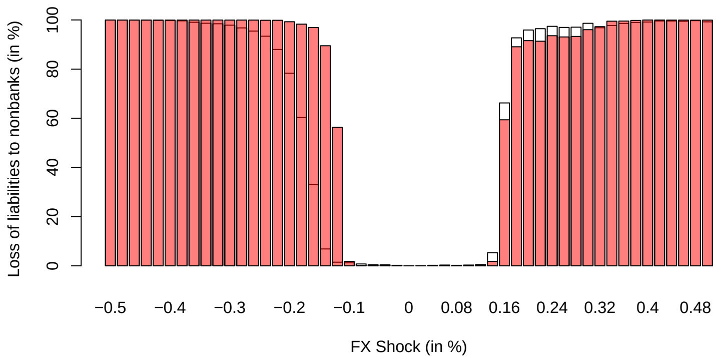
Figure 3: Greater nonbank assets and higher equity

Note: Subfigure (a) depicts losses in the baseline scenario (white) where $r_1 = 3/2$ and in an alternative scenario (red) where $r_1 = 5/2$. Subfigure (b) depicts losses in the baseline scenario (white) where $r_2 = 0.06$ and in an alternative scenario (red) where $r_2 = 0.08$.

(a) More domestic loans



(b) More foreign loans



(c) More domestic and more foreign loans

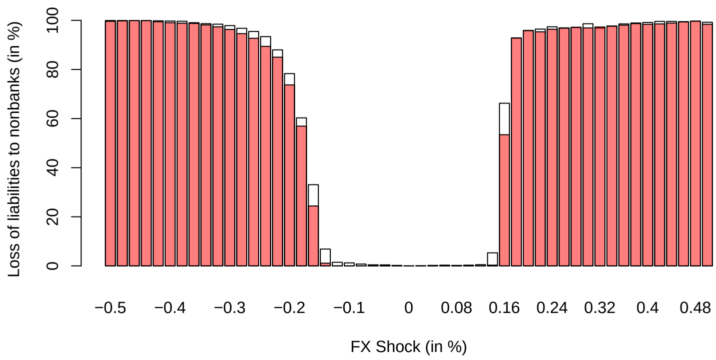


Figure 4: More interbank loans

Note: Subfigure (a) depicts losses in the baseline scenario (white) where $l = 10$ and in an alternative scenario (red) where $l = 30$. Subfigure (b) depicts losses in the baseline scenario (white) where $l' = 10$ and in an alternative scenario (red) where $l' = 30$. Subfigure (c) depicts losses in the baseline scenario (white) where $l = l' = 10$ and in an alternative scenario (red) where $l = l' = 30$.

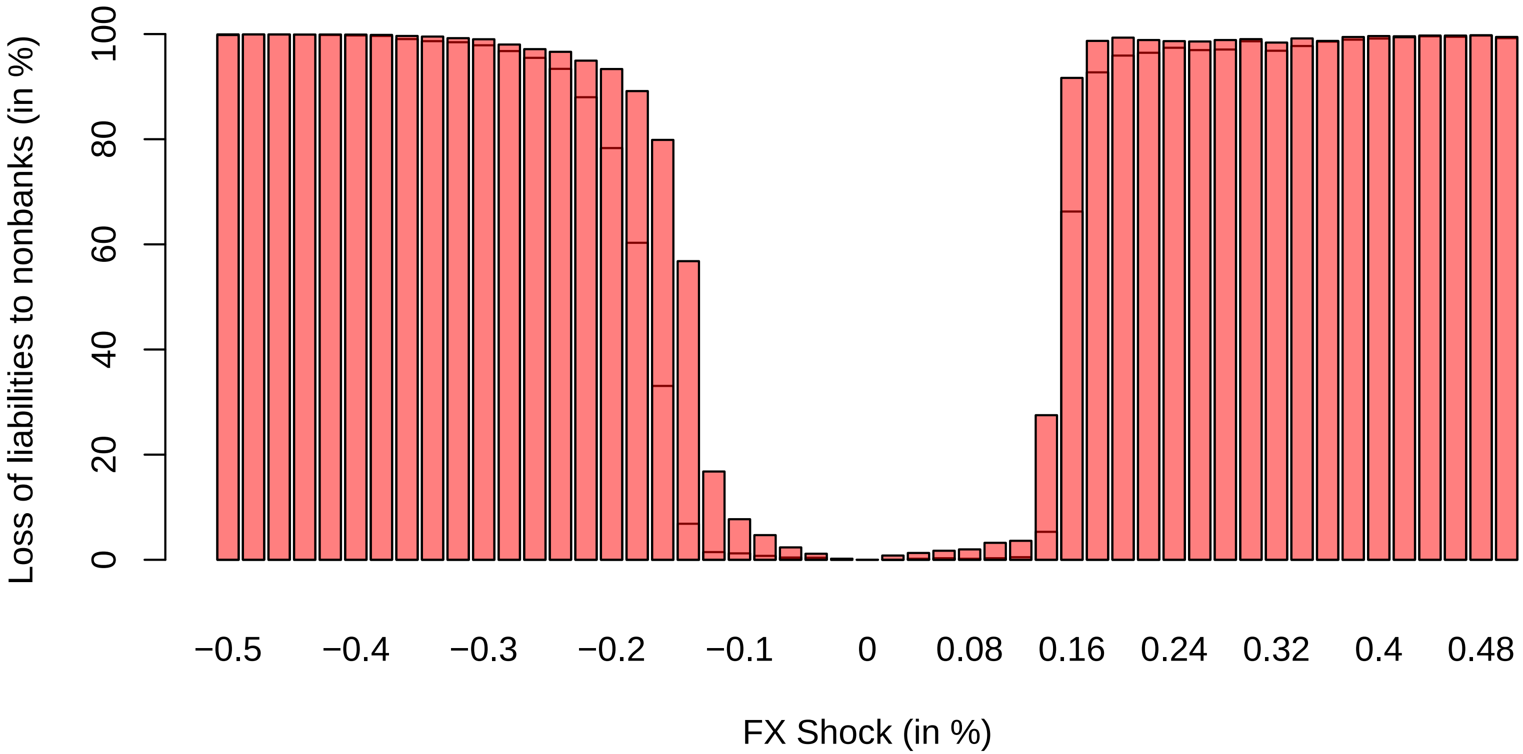
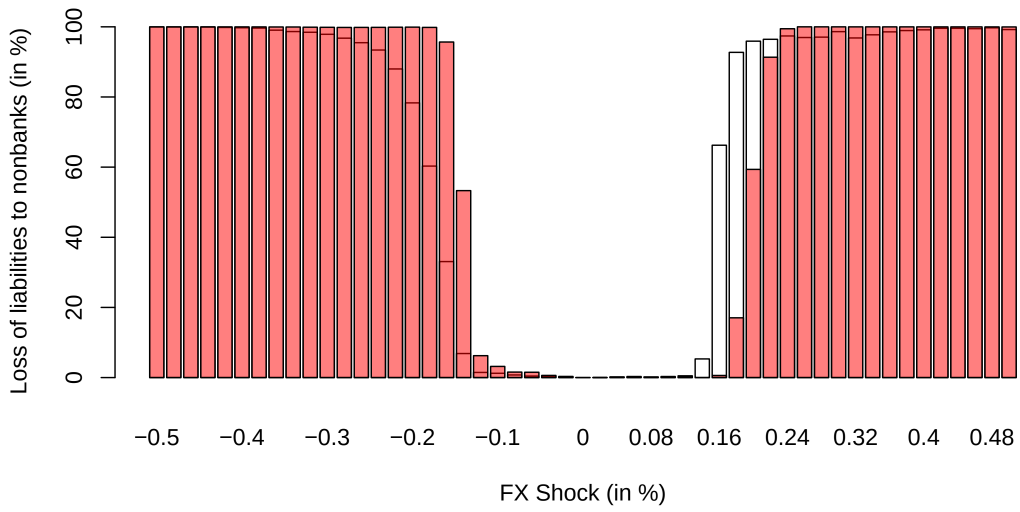


Figure 5: Greater interbank exposures

Note: The figure depicts losses in the baseline scenario (white) where $s = 2$ and in an alternative scenario (red) where $s = 8$.

(a) Shocks to dominant currency



(b) Shocks to other currencies

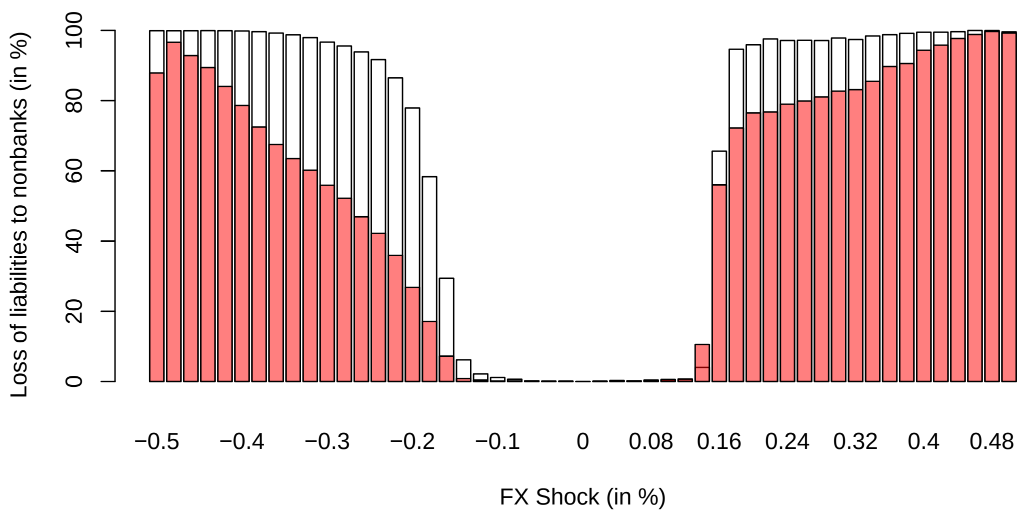
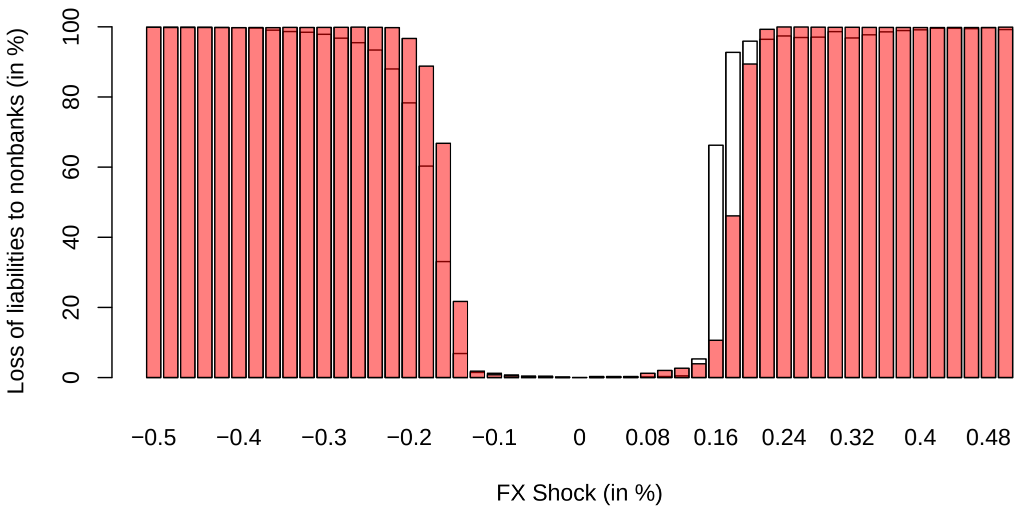


Figure 6: Asymmetry in bank location

Note: The two subfigures depict losses in the baseline scenario (white) where $D_1 = (0.25, 0.25, 0.25, 0.25)$ and in an alternative scenario (red) where $D_1 = (0.7, 0.10, 0.10, 0.10)$. Subfigure (a) shows the effects of exchange rate shocks to the dominant currency, while subfigure (b) depicts the effects of exchange rate shocks to any of the smaller currencies.

(a) Shocks to dominant currency



(b) Shocks to other currencies

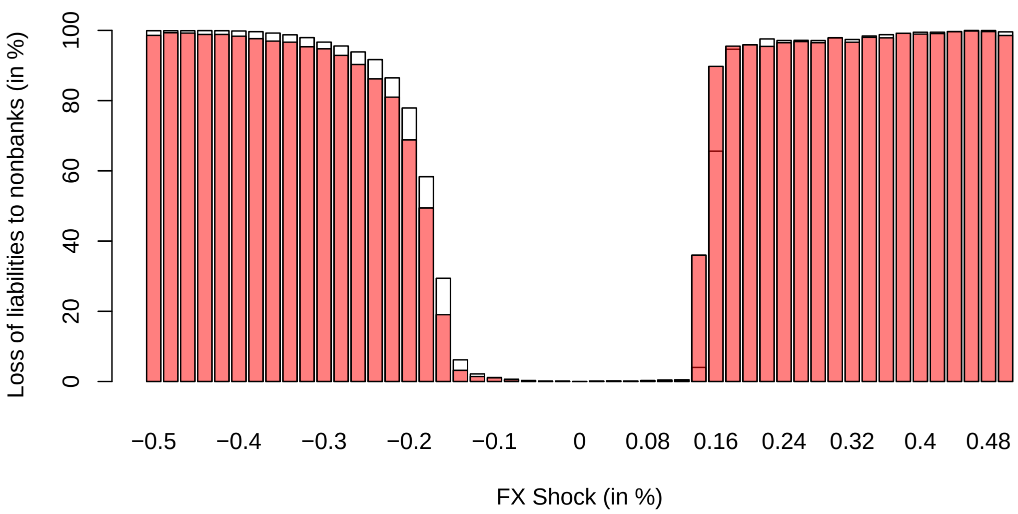


Figure 7: Asymmetry in interbank borrowing

Note: The two subfigures depict losses in the baseline scenario (white) where $D_2 = (0.25, 0.25, 0.25, 0.25)$ and in an alternative scenario (red) where $D_2 = (0.70, 0.10, 0.10, 0.10)$. Subfigure (a) shows the effects of exchange rate shocks to the dominant currency, while subfigure (b) depicts the effects of exchange rate shocks to any of the smaller currencies.

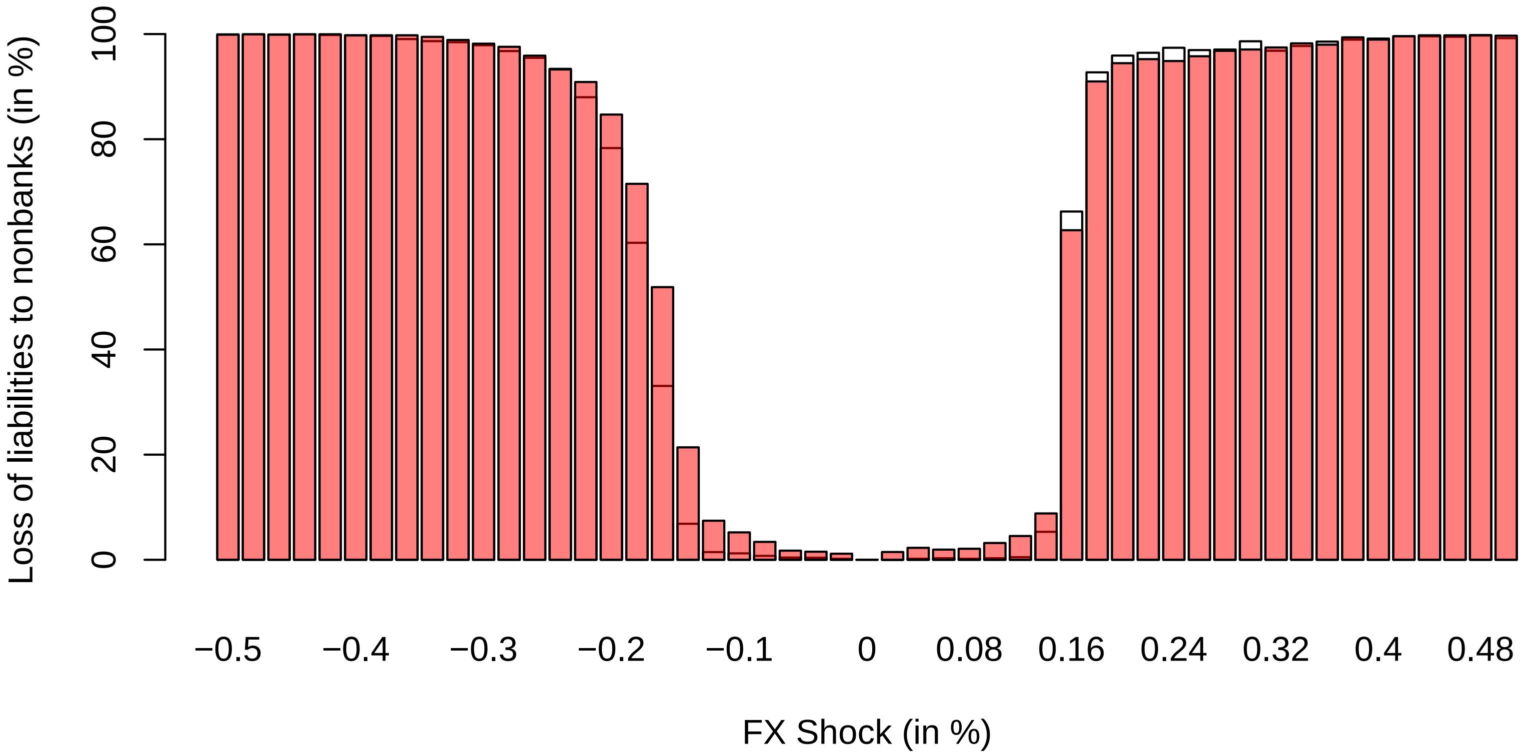
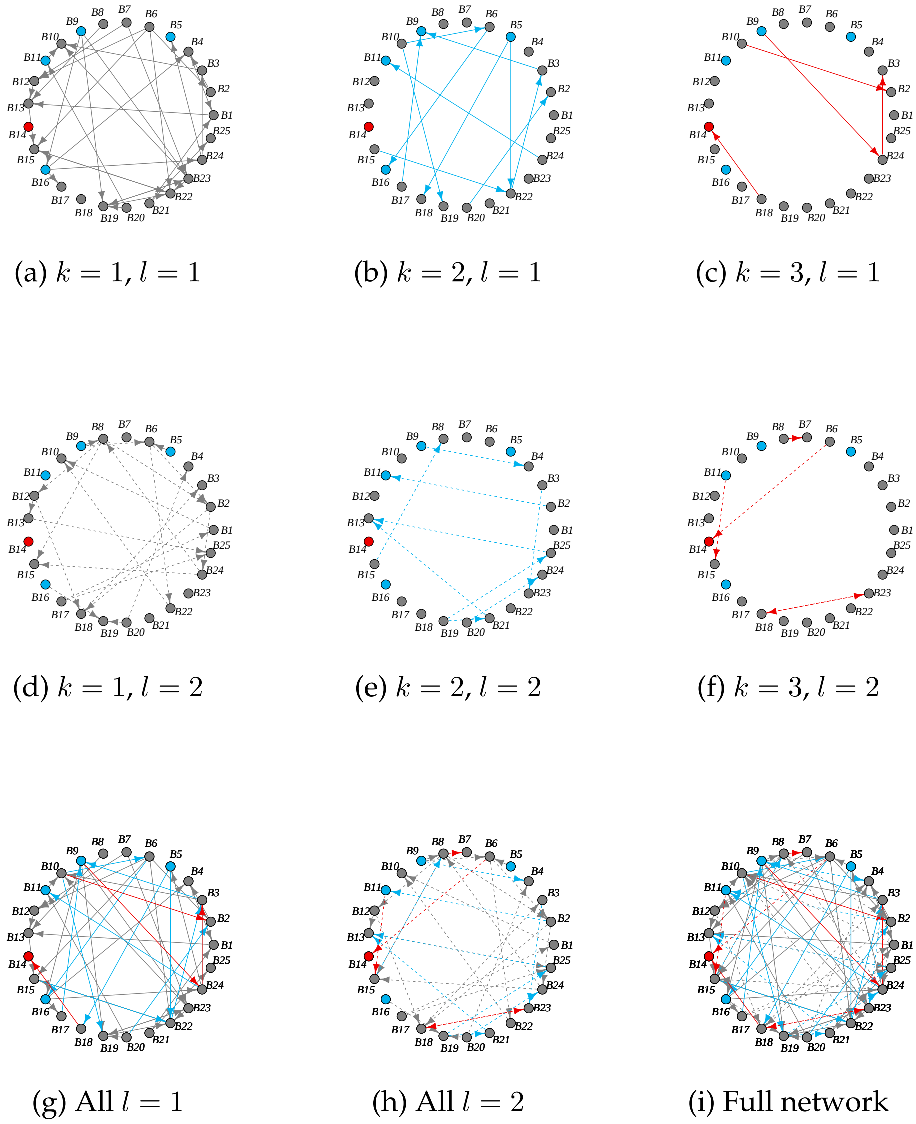


Figure 8: Bank breakups

Note: The figure depicts interbank losses in the baseline scenario (white) and an alternative scenario (red) where the 10 banks with the largest interbank liabilities are broken up into 20 smaller banks.



(a) $k = 1, l = 1$ (b) $k = 2, l = 1$ (c) $k = 3, l = 1$

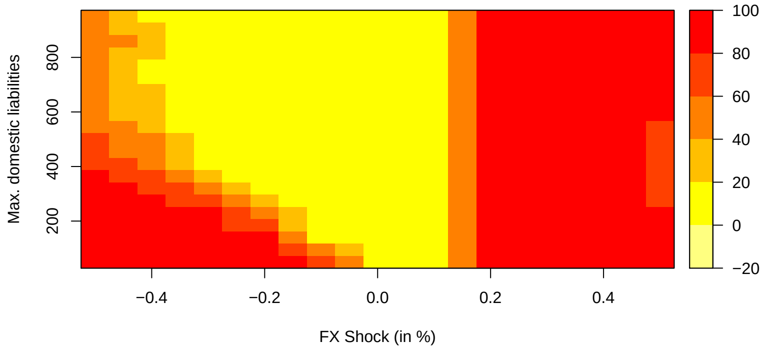
(d) $k = 1, l = 2$ (e) $k = 2, l = 2$ (f) $k = 3, l = 2$

(g) All $l = 1$ (h) All $l = 2$ (i) Full network

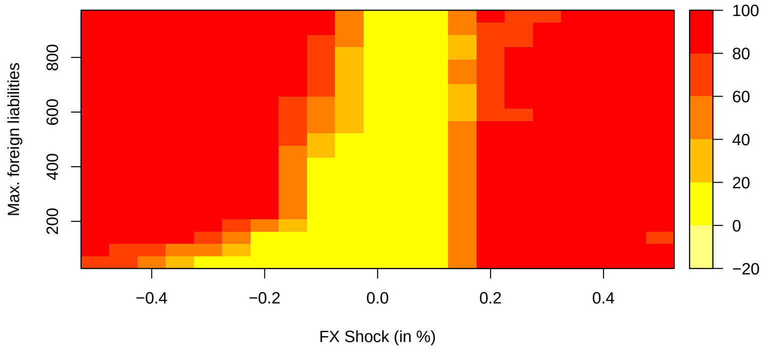
Figure 9: A multicurrency interbank market

Note: Nodes correspond to banks, edges to exposures. The different colors of the nodes resemble banks' different home currencies. Currency 1 is depicted in gray, Currency 2 in blue, and Currency 3 in red. Edges are colored the same way depending on the currency of the corresponding exposure. Arrows point from creditors towards debtors. Loans maturing in period $t + 1$ are depicted using solid lines. Loans maturing in period $t + 2$ are depicted using dotted lines.

(a) More domestic loans



(b) More foreign loans



(c) More domestic and more foreign loans

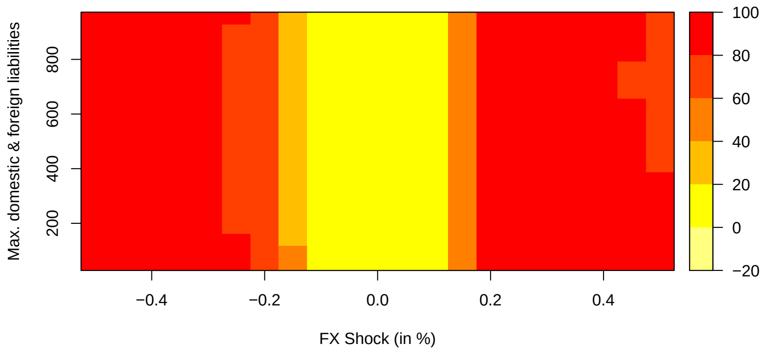


Figure 10: Sensitivity analysis of l and l'

Note: Subfigures (a) through (c) depict interbank losses as a function of the currency shock and l, l' and both of them, respectively. Bright colors indicate small losses, dark colors indicate large losses.

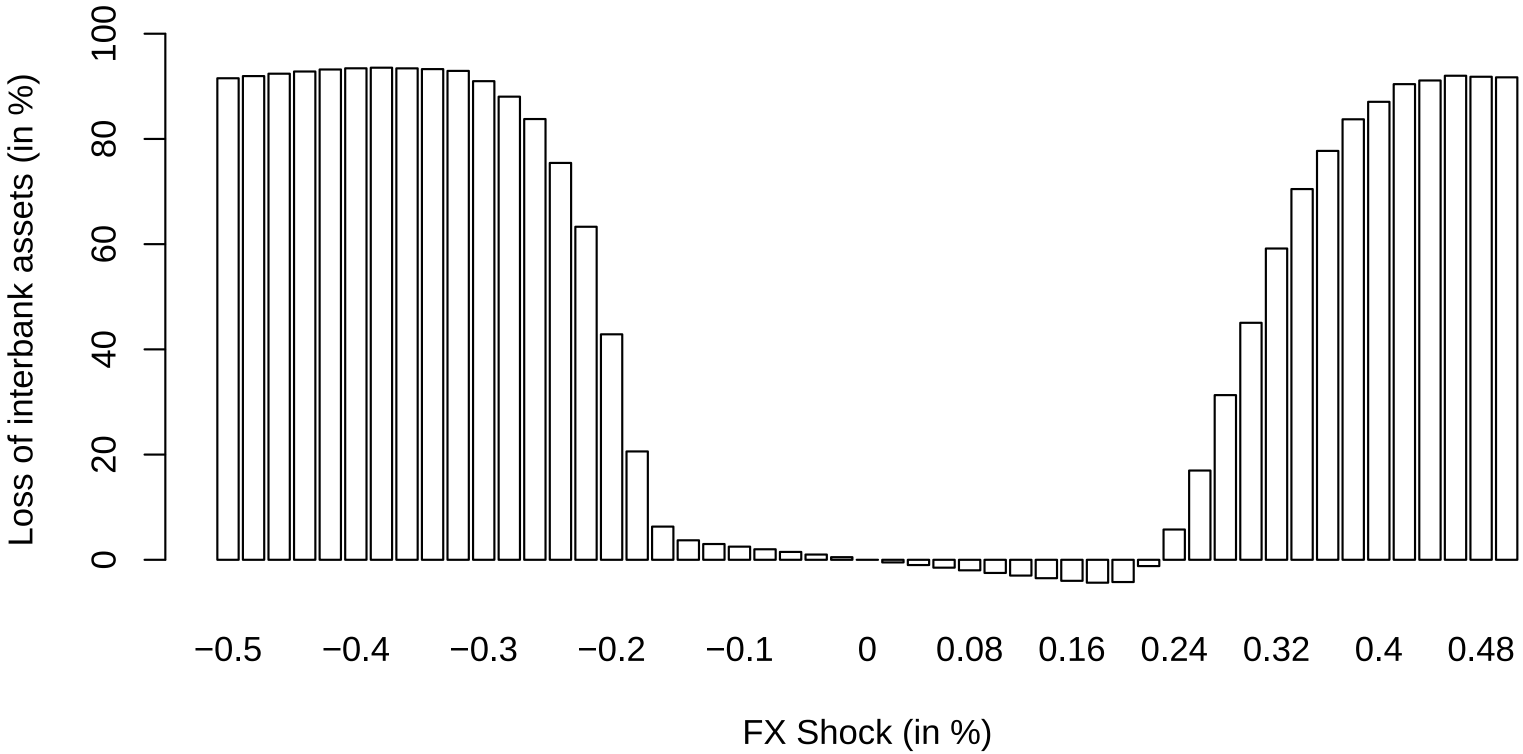
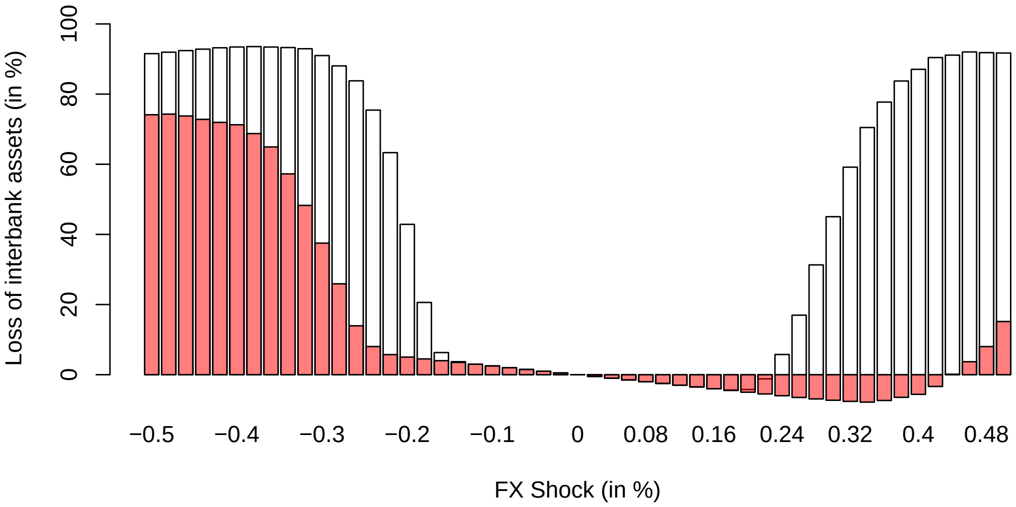


Figure 11: Baseline simulations

(a) Greater nonbank assets



(b) Higher equity

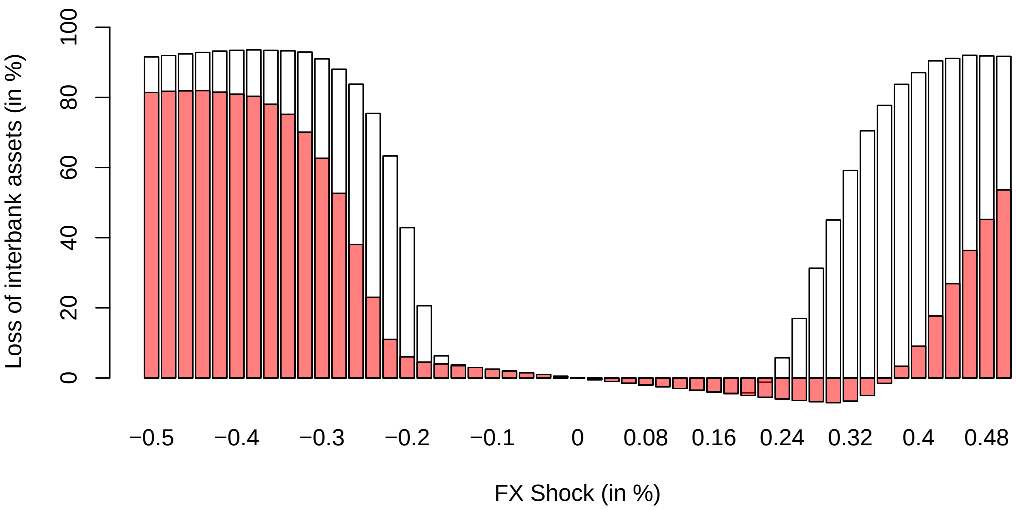
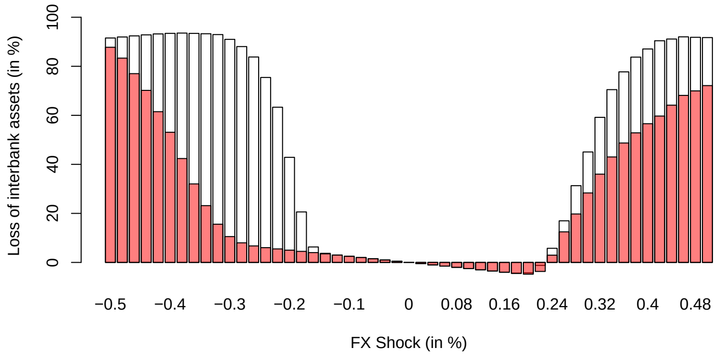


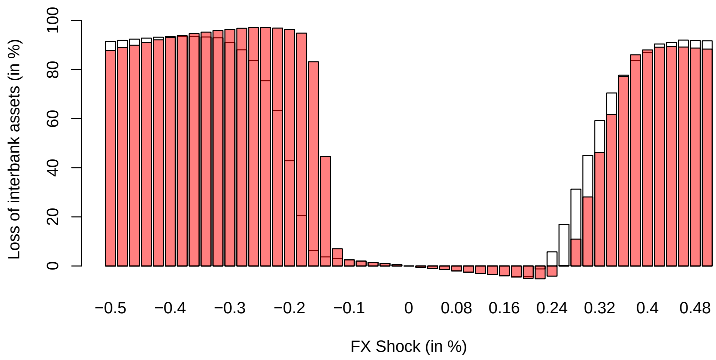
Figure 12: Greater nonbank assets and higher equity

Note: Subfigure (a) depicts interbank losses in the baseline scenario (white) where $r_1 = 3/2$ and in an alternative scenario (red) where $r_1 = 5/2$. Subfigure (b) depicts interbank losses in the baseline scenario (white) where $r_2 = 0.06$ and in an alternative scenario (red) where $r_2 = 0.08$.

(a) More domestic loans



(b) More foreign loans



(c) More domestic and more foreign loans

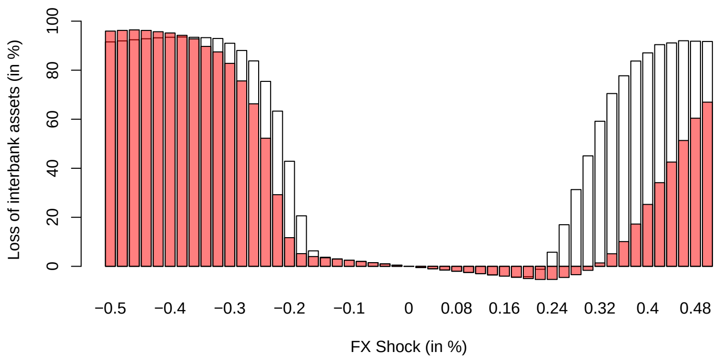


Figure 13: More interbank loans

Note: Subfigure (a) depicts interbank losses in the baseline scenario (white) where $l = 10$ and in an alternative scenario (red) where $l = 30$. Subfigure (b) depicts interbank losses in the baseline scenario (white) where $l' = 10$ and in an alternative scenario (red) where $l' = 30$. Subfigure (c) depicts interbank losses in the baseline scenario (white) where $l = l' = 10$ and in an alternative scenario (red) where $l = l' = 30$.

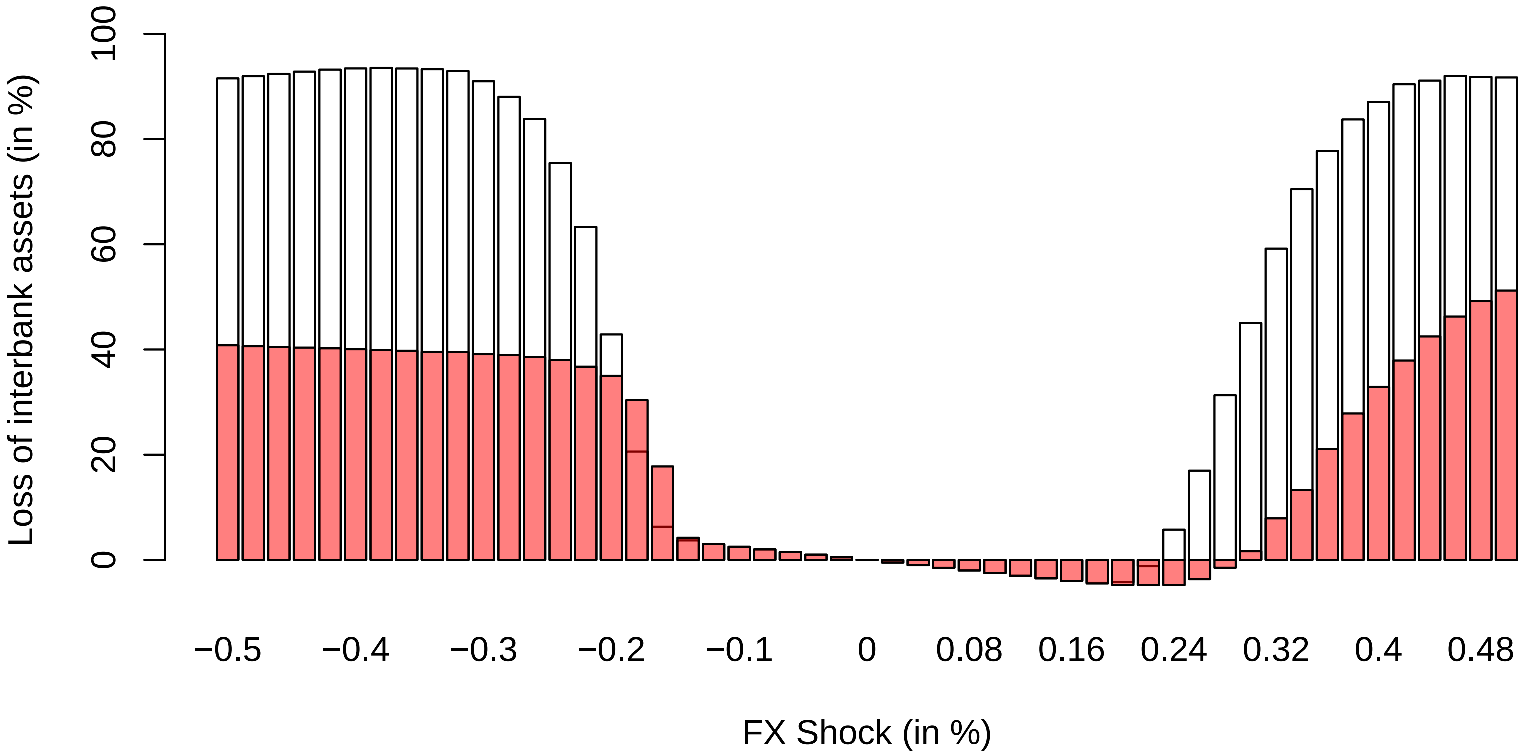
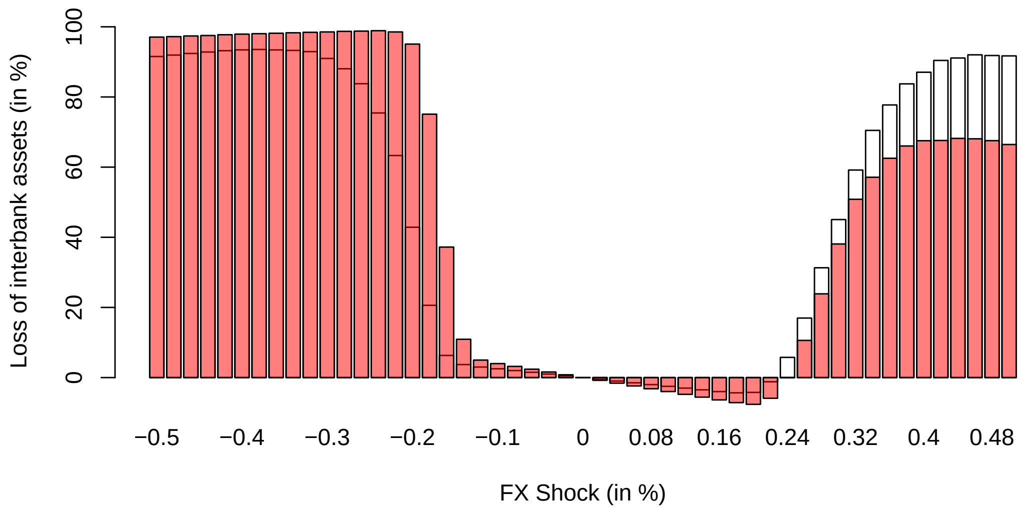


Figure 14: Greater interbank exposures

Note: The figure depicts interbank losses in the baseline scenario (white) where $s = 2$ and in an alternative scenario (red) where $s = 8$.

(a) Shocks to dominant currency



(b) Shocks to other currencies

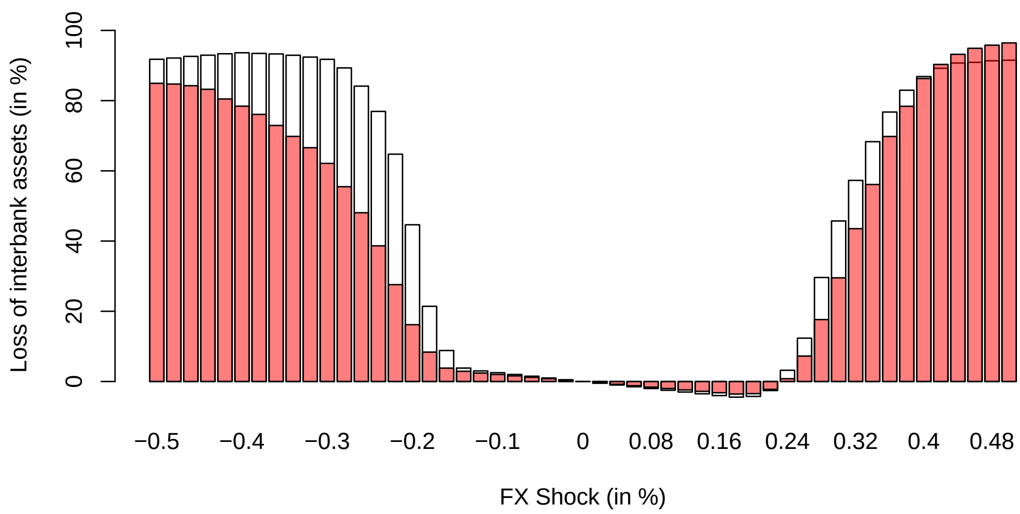
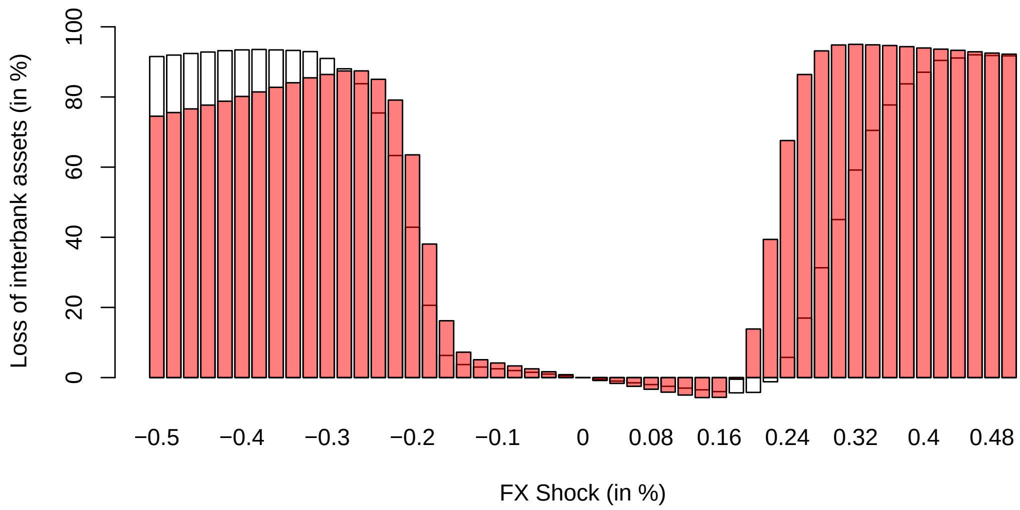


Figure 15: Asymmetry in bank location

Note: The two subfigures depict losses in the baseline scenario (white) where $D_1 = (0.25, 0.25, 0.25, 0.25)$ and in an alternative scenario (red) where $D_1 = (0.7, 0.10, 0.10, 0.10)$. Subfigure (a) shows the effects of exchange rate shocks to the dominant currency, while subfigure (b) depicts the effects of exchange rate shocks to any of the smaller currencies.

(a) Shocks to dominant currency



(b) Shocks to other currencies

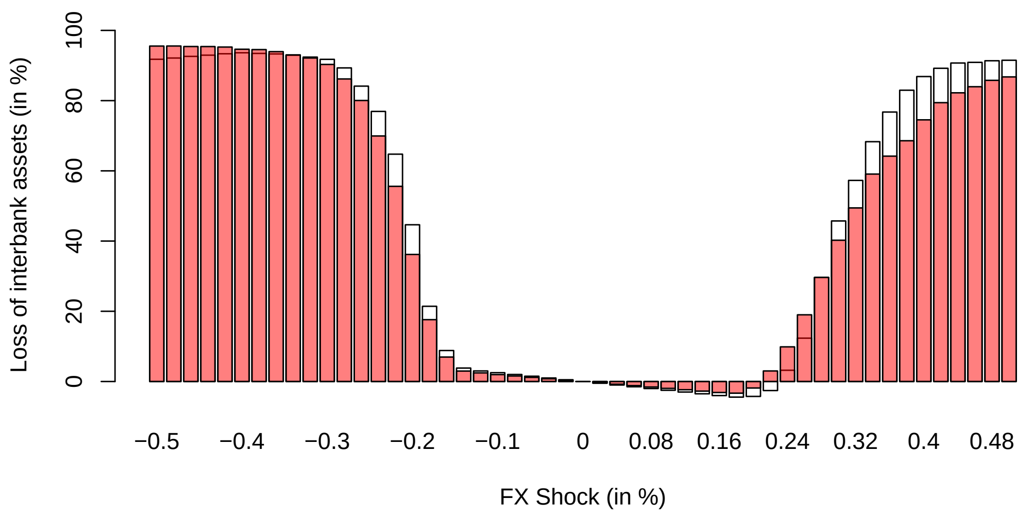
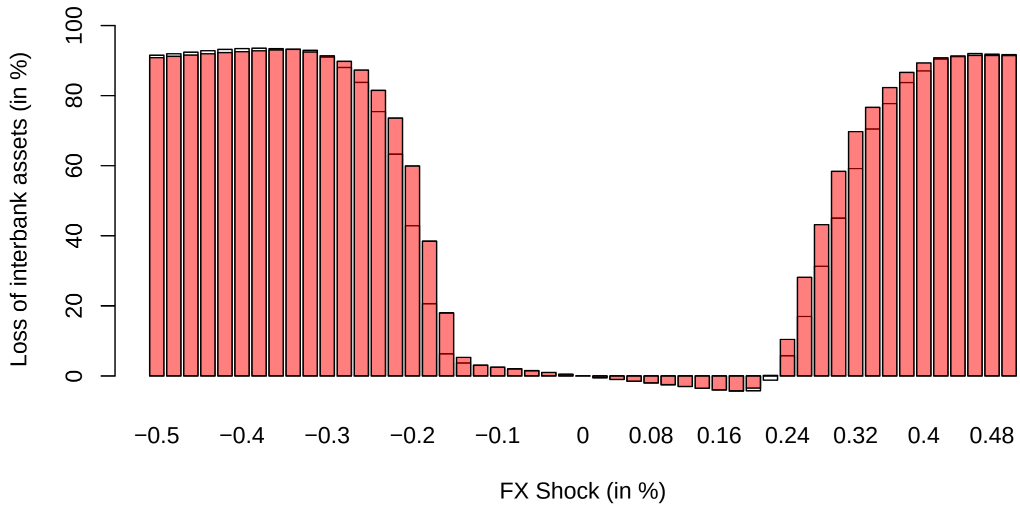


Figure 16: Asymmetry in interbank borrowing

Note: The two subfigures depict losses in the baseline scenario (white) where $D_2 = (0.25, 0.25, 0.25, 0.25)$ and in an alternative scenario (red) where $D_2 = (0.70, 0.10, 0.10, 0.10)$. Subfigure (a) shows the effects of exchange rate shocks to the dominant currency, while subfigure (b) depicts the effects of exchange rate shocks to any of the smaller currencies.

(a) Bank breakups



(b) Common equity pool

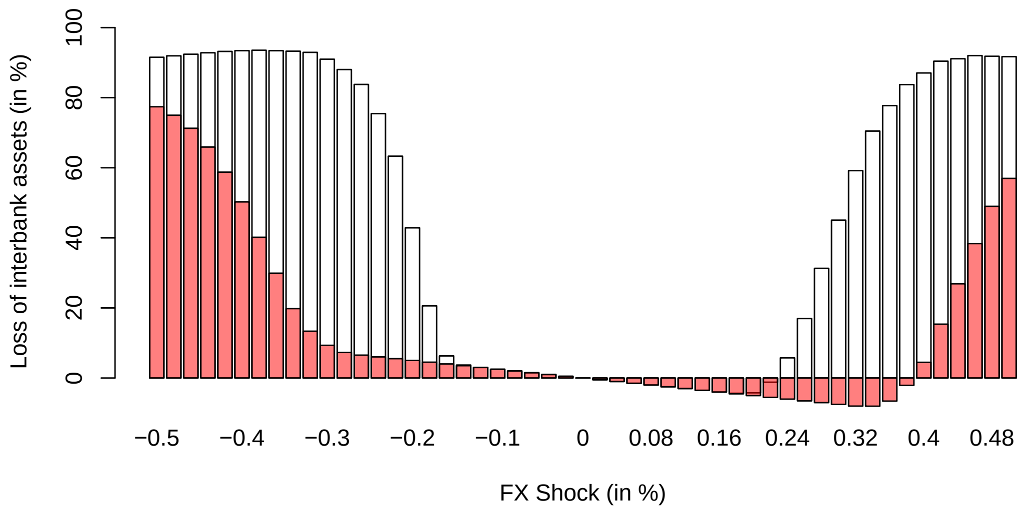


Figure 17: Policy interventions

Note: The two subfigures depict losses in the baseline scenario (white) and when conducting one of two policy interventions. Subfigure (a) shows the effects of exchange rate shocks when the 10 banks with the largest interbank liabilities are broken up into 20 smaller banks. Subfigure (b) shows the results when banks commit five percent of their equity to a common equity pool.