Prêmio
Banco Central de Economia e Finanças

Estabilidade Financeira • 2º lugar

Measuring Systemic Risk under Monetary Policy Shocks: a network approach

Thiago Christiano Silva
Solange Maria Guerra
Michel Alexandre da Silva
Benjamin Miranda Tabak

thiago.silva@bcb.gov.br
solange.guerra@bcb.gov.br
michel.alexandre@bcb.gov.br
benjaminm.tabak@gmail.com

Brasília • 2016

BANCO CENTRAL DO BRASIL

Measuring Systemic Risk under Monetary Policy Shocks: a network approach

Thiago Christiano Silva*

Solange Maria Guerra**

Michel Alexandre da Silva ***

Benjamin Miranda Tabak****

Abstract

We develop a novel approach to evaluate the impact of monetary policy shocks on the economy, with contagion, illiquidity spirals and amplification components. We study the short-term effect of monetary policy surprises on a multilayer network, which comprises interbank lending and loans made by banks to nonfinancial firms. Our results suggest that bank type (state-owned, domestic private, and foreign private) matters for the systemic risk buildup. We find that systemic risk components vary across different economic sectors, with primary and fabricated metal, tertiary, and food & beverage being the most sensitive sectors in the short term to monetary policy shocks. We identify an asymmetric profile in the economic sectors' sensitiveness to these monetary policy shocks that arises due to bank hedging. We find that monetary policy shocks can have linear and non-linear reflections on the short-term systemic risk in the economy, depending on the shock magnitude. In particular, we show that big swings in the monetary policy can cause undesirable non-linear consequences on the financial stability of the economy.

Keywords: monetary policy, financial stability, systemic risk, financial accelerator, contagion, real sector.
JEL Classification: G01, G21, G28, C63.

*Research Department, Banco Central do Brasil, e-mail: thiago.silva@bcb.gov.br
**Research Department, Banco Central do Brasil, e-mail: solange.guerra@bcb.gov.br
***Financial System Monitoring Department, Banco Central do Brasil, e-mail: michel.alexandre@bcb.gov.br
****Universidade Católica de Brasília, e-mail: benjaminm.tabak@gmail.com

1 Introduction

Since the crisis of 2008, there is an ongoing debate on the role of interconnectedness in the amplification of shocks through contagion. In this spirit, several papers have attempted to estimate different systemic risk measures using information on financial networks.[1] Nonetheless, in the majority of these papers, there is no role for the Central Bank. Central banks use monetary policy to achieve its inflation target goals, which may be explicit or implicit. These monetary shocks can have disrupting impacts on financial stability. Although this is a relevant issue, so far there is a gap in the literature.

It is not clear how monetary policy may have adverse impacts on financial stability and how it may affect different economic sectors, which rely on credit to finance their operations. Different economic sectors have diverse sensitivities to monetary shocks, due to disparities regarding market structure, competition, leverage ratios, portfolio duration, access to the credit market, among others characteristics. If an economic sector suffers a major impact due to monetary policy shocks—which could be transmitted by a diversity of financial channels and conditions—then we would observe an amplification and contagion process within the real sector that would feedback into the financial sector.

The extent of the problem depends on the specific characteristics of the economy, its financial sectors and how reliant firms are on banks to finance their operations. We add to the debate by not only proposing a model to assess systemic risk in face of monetary policy shocks but also by estimating their impact on a variety of economic sectors for the Brazilian economy. With the help of a very thorough database that contains detailed information on all loans made by banks to firms and between banks themselves, we are able to estimate this impact and thus evaluate the implied systemic risk of monetary policy shocks in different periods.

Our work represents an original research that addresses very relevant questions: how do monetary policy shocks affect the real sector and the economy's financial stability as a whole? What is the measure of systemic risk in face of monetary policy shocks? Which economic

[1] Methods that use financial networks to estimate systemic risk normally fall into two broad categories: either they use Eisenberg and Noe (2001)'s or Battiston et al. (2012)'s propagation mechanism. While the first evaluates real losses for a given shock, the second measures financial stress inside the network, which can or cannot materialize. Silva et al. (2017b) provides a review on the differences of these methods.

sectors have larger systemic risk implications? What is the role of interconnectedness in transmitting monetary policy shocks to different financial and nonfinancial firms? These questions are of utmost importance for the design of policies that take into account both dimensions—macroeconomic stability and financial stability.

The literature argues that the deficient regulatory framework was one of the main drivers that led to the unseen systemic risk buildup in the global financial system in the first decade of 2000 (Steiner (2014)). At the time, the regulatory framework was concerned predominantly with microprudential issues. In the aftermath of the crisis, in contrast, there seems to be agreement among both academics and policymakers that financial regulation needs to shift towards a macroprudential direction when regulating for financial stability (Acharya et al. (2014); Hanson et al. (2011)).[2]

Financial stability and systemic risk have become crucial research topics after the global financial crisis, which in turn has highlighted how complex financial networks are interconnected (Battiston et al. (2016)). Targeted shocks on a specific market can trigger large disruptions in the entire economic environment, as economic agents are intertwined in several markets through financial operations. In this spirit, Gai et al. (2011) illustrate how complexity and concentration in financial networks can amplify fragility and thus contribute to financial instabilities. Such interconnectedness property leads to the emergence of potential and nontrivial contagion transmission channels between economic agents and hence raises the difficulty in understanding how financial stability evolves in the economy. Diligently, the International Monetary Fund, the Financial Stability Board, and the G20 (IMF et al. (2009)) have recognized interconnectedness as an essential determinant of systemic risk buildup and hence financial instability.[3] Therefore, network-based models have gained increased attention as they are suitable mathematical tools that can adequately characterize the complex interconnectedness that arises

[2]Microprudential regulation aims at preventing the costly failure of individual financial institutions. By contrast, a macroprudential approach recognizes the importance of general equilibrium effects, and seeks to safeguard the financial system as a whole.

[3]These international entities report three key criteria that are essential in identifying the systemic importance of markets and financial institutions to the stability of the financial system: size, substitutability, and interconnectedness. Size refers to the volume of financial services provided by the individual component of the financial system. Substitutability measures the extent to which other components of the system can provide the same services in the event of a failure. Finally, interconnectedness accounts for the linkages with other components of the system and how shocks transmit between different markets or financial institutions.

among economic agents.

Though the theory of networks has been extensively applied to financial networks, the literature still lacks a general model that links how monetary policy decisions affect heterogeneous economic agents due to the "network effect." For instance, it is long known that monetary policy first impacts the financial sector for only then to reflect into the real sector. In this paper, we contribute with a model that explicitly takes into account this sequential ordering when addressing the link between monetary policy and financial stability.

Papers dealing with monetary policy normally investigate its long-term effects on the economy. For instance, Bernanke and Blinder (1992) target the macroeconomic aspect of monetary policy by examining the strength of the federal funds rate as a tool of monetary policy to adjust output and price using a vector autoregression model. In turn, Jiménez et al. (2014), Dell'Ariccia et al. (2014), and Maddaloni and Peydró (2011) study the effects of monetary policy on credit risk-taking in environments of prolonged low interest rates.

Researches that mainly deal with financial stability, in contrast, focus on the role that financial networks play in amplifying losses in face of external perturbations. For instance, Acemoglu et al. (2015) show that contagion in financial networks exhibits a form of phase transition. In this respect, more densely connected networks enhance financial stability as long as the magnitude of the negative external perturbation is sufficiently small. However, beyond a certain critical point, dense interconnections serve as a medium that favors propagation of shocks, leading to more fragile financial systems. In the same vein, Elliott et al. (2014) study cascades of failures in financial networks and find that the effects of increasing dependence on counterparties (integration) and more counterparties per organization (diversification) have different and nonmonotonic effects on the extent of financial contagion.

All of these works leave aside the risk sensitiveness of economic agents to actions of the policymaker. Therefore, on the one side, papers that explore monetary policy are generally concerned with its long-term effects and the potential transmission channels and relegate the fact that economic agents are interconnected and thus subject to negative spillover effects. On the other side, researches lying in the financial stability domain account for the interconnectedness of economic agents but are short in bringing in the role of the policymaker in its goal of conducting monetary policy. Our work attempts to bridge that gap between monetary policy and financial stability in the risk dimension while accounting for the interconnectedness aspect that is strongly present in the economy.

Our contribution may be useful for central banks to conduct monetary policy while accounting for safeguarding the economy from systemic collapses. In this respect, our model provides quantitative insights of which sectors in the real economy or types of banks would suffer more or be better off from a tightening or loosening of monetary policy. In addition, central banks can employ the proposed framework to subside decisions regarding the management of the interest rate not only to warrant price and output stability but also to target the reduction of the systemic risk buildup in the economy.

We design our framework using multilayer financial networks, in which each layer comprises a set of economic agents of the same nature. The financial sector layer encompasses the collection of banks in the economy, the real sector layer includes firms, and the policymaker layer embodies the central bank. Each of these economic agents has heterogeneous loss absorbing capabilities, which we proxy by its equities, and responds differently to financial stress shocks coming from their counterparties. We capture this bilateral sensitiveness by inspecting how critical an individual debtor counterparty is with respect to the creditor's equities should that counterparty not honor its liabilities.

There are financial operations linking pairs of economic agents that may reside in the same or in different layers. In the financial sector layer, banks participate in the interbank market via lending and borrowing operations. In the real sector layer, firms potentially hold accounts payable against each other as a consequence of goods or services on credit they purchase from other firm suppliers. Linking the financial and real sector layers, firms borrow from banks to finance their projects and boost their production and profit levels while banks hold securities from these firms. We also have the policymaker layer, which only connects to the financial layer to model the bank sensitiveness to innovations in monetary policy decisions. We do not maintain direct links between the policymaker and firms to represent the fact that monetary policy only affects the financial sector a priori. However, as bank risk perception accommodates to the new environment, the effects of monetary policy indirect transmit to the real sector.

Each of these financial operations potentially creates contagion transmission channels that propagate to economic agents residing in the same or different layers. We build upon Silva et al. (2017a)'s model of systemic risk that only considers the propagation of shocks in the real and the financial sectors. The model explicitly takes into account the feedback effect of shocks on economic agents. In this respect, the authors model a financial accelerator engine (Bernanke (1983); Bernanke and Gertler (1989); Bernanke et al. (1996)) in a network environment to account for the contagion transmission channel between the real and financial sectors.[4]

We improve Silva et al. (2017a)'s model by bringing in the central bank as an economic agent and by explicitly estimating the sensitiveness of banks to shocks of the central bank in face of monetary policy actions. This sensitiveness also creates another transmission channel between the central bank and the financial sector. We now describe these transmission channels linking i) the real and financial sectors and ii) the financial sector and the central bank.

In the first channel, when firms cannot fulfill their obligations to their creditor banks, these banks become potentially distressed in view of assets write-offs. Such reduction places upper bounds on bank assets and thereby on bank lending on account of regulatory capital constraints. Thus, the increase in the stress levels of banks feedbacks to the real economy through a credit crunch, which then exacerbates the initial shock on firms. Closing the amplifying cycle, firms are further stressed owing to the credit availability constraints imposed by banks, leading them into reduced levels of investment and consumption. This negative effect on firms' production levels causes a potential decrease in profit, which is then transmitted back to banks in the form of loan defaults.

In the transmission channel linking the central bank and the financial sector, we estimate bank sensitiveness to variations of the policy interest rate at the individual level. As we are dealing with systemic risk issues, we focus on the short-term consequences of interest rate adjustments on banks' loss absorbing capabilities, i.e. bank equities.[5] The rationale here is that, once banks have their equities altered by interest rate variations, they propagate forward

[4]The idea of a financial accelerator comes from the fact that the borrower amplifies an initial negative shock by further decreasing its investment and production activities.

[5]Several works show that monetary policy affects the course of the financial and real sectors (Bernanke and Gertler (1995); Dell'Ariccia and Marquez (2006); Diamond and Rajan (2012); Hubrich and Tetlow (2015); Stein (2012)).

this financial distress to other banks and firms. In this way, we can capture to what extent economic agents become distressed as a consequence of interest rate innovations. We now present arguments that characterize how monetary policy can affect bank equities or capital through variations of the policy interest rate.

There are two broad channels through which interest rate shocks may directly affect banks (Kashyap and Stein (2000)): the risk-taking channel and the credit channel. Interest rate changes act on at least one of the components of banks' capital adequacy ratio, namely, the capital level or the risk-weighted assets.

The risk-taking channel refers to the impact of prolonged accommodative monetary policy on the risk perception and tolerance of banks through the "search-for-yield" mechanism and the impact on valuations, incomes and cash flows that may decrease the banks' probability of default and thus incentive more risky positions (Bruno and Shin (2015); Dell'Ariccia et al. (2014); Eser and Schwaab (2016); Jiménez et al. (2014); Maddaloni and Peydró (2011)).[6] Our model does not capture bank risk-taking because we do not allow the network to change endogenously through agents' decisions of establishing or severing a financial connection. In this sense, our model is suitable to understand the short-term consequences of a monetary policy shock. In addition, in our empirical application using Brazilian data, it becomes difficult to defend the existence of such a channel because Brazil's interest rate have remained historically high.

In turn, the credit channel can be further subdivided into two classes (Ashcraft and Campello (2007); den Haan et al. (2007); Disyatat (2011); Jiménez et al. (2012)): the bank lending channel and the balance-sheet channel. The bank lending channel relates to the opportunity cost of bank liabilities. For instance, rises in interest rate makes government bonds more attractive in detriment to bank loans, which may ignite a substitution effect of loans to government bonds. Such a channel takes time to occur mainly because they involve operations with other counter-

[6]In the "search-for-yield" mechanism, low nominal interest rates may increase incentives for asset managers to take on more risks for contractual, behavioral or institutional reasons when i) interest rates are close to zero and ii) there are prolonged periods of low interest rates. Monetary policy can also impact valuations, incomes and cash flows. In this aspect, a reduction of the policy rate boosts asset and collateral values, which in turn can modify bank estimates of probabilities of default, loss given default and volatility. As volatility tends to decline in rising markets, it releases risk budgets of financial firms and encourages position-taking. For this mechanism to be at work it is essential that banks use internal models.

parties. As we consider the network as exogenous, we also do not account for this channel.

The balance-sheet channel, in the short run, works through changes in the banks' trading book values as a result of daily mark-to-market of assets and liabilities.[7] This valuation change impacts bank capital as banks must immediately recognize the monetary differences on their trading books in their profits and losses accounts due to daily mark-to-marketing. Since the reflection of interest rate changes on banks' balance sheets is immediate, as they are legally enforced to mark-to-market instruments of the trading book, this is the main transmission channel that we use to understand the short-term effects of monetary policy shocks in the economy.

In addition, Basel III recommends to compliant countries that banks meet minimum capital requirements on a continuous basis (BCBS (2015)). Therefore, the instantaneous changes on banks' trading book values are the component that concerns us here, mostly because systemic risk and financial stability presupposes instantaneous shocks and short-term aftereffects. For instance, some banks may immediately run into insolvency signals due in view of market variations and hence impair stability of the entire financial system should they have several creditor counterparties.

The problem with large variations of banks' trading books as a consequence of high market sensitivity may be troublesome. In this aspect, Basel III strictly limits the ability of banks to move instruments between the trading book and the banking book by their own choice after initial designation, so as to bypass financial regulation requirements and recover from accounting losses (BCBS (2015)). In practice, switching is rare and allowed by regulators only in extraordinary circumstances. Therefore, the immediate impact on banks' capital levels in light of updates on their trading book values stands as a relevant short-term contagion transmission channel triggered by monetary policy that we explore in this work.

The share of investments that banks maintain in the trading and in the banking books depends on their natural preponderant activities. Investment banks normally take on more risks and therefore are more susceptible to changes in the interest rate. Following Benoit et al. (2017), we denote as "systemic risk-taking" the component of banks that relate to how sensitive they

[7] The trading book should contain trades with intent of making profit through market price movement, holding for short term resale, locking in arbitrage profit or hedging other trading book positions. Instruments in the trading book must be mark-to-market daily. In contrast, the banking book should contain positions with intent of holding until maturity. In this case, they do not need to mark-to-market daily.

are to interest rate shocks. To estimate this sensitiveness, we first consider that monetary policy shocks change the term structure of the interest rate. Then, to get a comprehensive view on the systemic risk-taking of banks, we evaluate the changes in their net exposures for instruments maturing from 1 day to 30 years in the term structure.

Our paper is also innovative in terms of how we conduct the contagion analysis in face of monetary policy shocks. For instance, the policymaker can increase or decrease interest rates and each of these actions reflects in different ways on banks' capital levels. Depending on the trading book sizes on the liability and asset sides, some banks may be better off while other can suffer decreases in their capital levels. Banks that are better off can expand credit to the real sector while negatively impacted banks can apply credit crunches. Then, a firm can face a credit expansion and a credit crunch from different bank counterparties, such that the opposing effects cancel out in the aggregate. To the best of our knowledge, this is the first work in the financial contagion literature that accounts for propagation of positive shocks in a network comprising economic agents.

We empirically analyze the short-term sensitiveness of Brazilian banks and firms using several data sets, including the Brazilian credit register that holds millions of financial operations. We divide our results in two parts, which follow the model's rationale. Regarding the systemic risk-taking component, we show that the absolute bank net worth variation in face of an absolute 10% change in the interest rate is up to 2%. In the majority of the cases, an increase in the interest rate brings losses to the banks in the form of net worth reduction, unveiling a systemic risk-taking behavior attached to interest-rate fluctuations. State-owned banks, especially the large ones, are less sensitive to interest rate changes, while large foreign private banks are the more sensitive ones.

When we consider the financial contagion throughout the real and financial sectors, nonlinearities arise: for both the financial and the real sectors, the relationship between the systemic risk and the interest rate shock is linear when the absolute value of the shock is below a certain level. After this point, such relation becomes exponential. Large banks are more susceptible to financial contagion than small/medium ones. Moving to the real sector analysis, food and beverage, primary and fabricated metal, tertiary, and chemical are the most sensitive sectors to interest rate shocks and construction, electric power, pulp and paper, and technology sectors are the less sensitive ones.

The impact of monetary policy on financial stability has been extensively discussed, mainly after the 2008 financial crisis (see, e.g., Stein (2012)). Nonetheless, the question as to how such relationship can be shaped by financial networks, with few exceptions, has been neglected. In the models developed by Georg (2013) and Bluhm et al. (2014), the central bank acts as a liquidity provider in an interbank network. The difference is that, in the former case, liquidity is provided against eligible collateral, while it is unlimited in the latter. Liquidity provision makes banks more resilient to shocks, but is detrimental to financial stability in the sense that it encourages risk-taking behavior (Bluhm et al. (2014)) and results in a more interconnected financial system, in which shocks are more easily propagated (Georg (2013)). Our paper contributes to this literature in at least two ways. First, no other study has analyzed the effects of monetary policy in a multilayer financial network. Besides the interbank market, we consider also a bivariate network in which firms borrow from banks. Second, in addition to the theoretical model, we perform an empirical analysis using Brazilian data.

2 Methodology

In this section, we discuss the intuition and underpinnings of our methodology.

2.1 Intuition of the model

Our economy comprises the real and the financial sectors as well as the policymaker, which can apply interest rate shocks to conduct its monetary policy. The financial sector has banks that hold exposures against each other through interbank borrowing and lending relationships. The real sector encompasses firms that can take purchases on credit of supplies and/or services and thus become exposed to each other. In addition, firms can invest in bank bonds and banks can grant loans to firms that meet their screening standards. Credit to counterparties generates financial exposures that link balance sheets of different economic agents, thus making them susceptible to financial contagion and amplification.

Our model is particularly useful for understanding the very short-term consequences of these shocks in the economy, in that it assumes that the network topology does not change after the shock.[8] Equities are the main resource economic agents employ to withstand unexpected losses. As such, a decrease in their net worth/equities puts them into a more fragile state and hence push them towards the insolvency state. Our model uses this reduction of the economic agents' net worth to estimate the implied systemic risk of an interest rate shock by essentially evaluating how close each economic agent gets to insolvency.

The model has two steps:

1. *The systemic risk-taking component*: the policymaker applies an interest rate shock (increase or reduction). Banks face an immediate effect on their net worth through the profit and loss account as a result of variations of their trading (mark-to-market) assets and liabilities. Depending on their net exposures, they can gain or lose money out of this interest rate shock. Banks with larger trading book portfolios are potentially more susceptible to changes in the policy interest rate.[9]

2. *The financial contagion and amplification components*: the negative or positive variation of banks' net worth have implications for the real sector in the form of credit reduction or expansions. In case of a credit crunch, some affected firms may not be able to sustain their current operational levels and must readapt their activities. These actions reflect in lower profit levels and therefore these firms become financially distressed as well. Alternatively, in case of a credit expansion, firms are able boost their sales through the facility of bank financing and hence their net worth increases. In either case, the shock gets amplified and bounces back to the financial sector in a real negative or positive feedback mechanism. This feedback mechanism gives rise to a micro-level financial accelerator that is fueled by these positive or negative stress propagation spirals. To illustrate, let us suppose a positive monetary policy shock that causes a decrease in the net worth of a bank. Then:[10]

[8] To understand the medium- and long-term effects of monetary policy shocks in the economy, we would have to consider the network topology as endogenous. In this configuration, each bank and firm would be allowed to create and sever links to each other based on their utility functions.

[9] A large trading book does not necessarily imply more systemic risk-taking by banks. For instance, banks can hedge their positions against variations of the interest rate. Our framework captures this issue when estimating the banks' net worth sensitiveness.

[10] We can apply a similar reasoning in case of a credit expansion for banks that are better off after the monetary

(a) The decrease in the bank' net worth leads to a reduction of credit to the real sector. This reduction is caused in part by (i) the substitution effect of risky assets (loans to the real sector) to less risky and now more attractive government bonds and (ii) the reduction of its risk-weighted assets to comply to the daily macroprudential regulatory rules.

(b) Due to this credit restriction, some firms are not able to roll over their short-term debt towards the financial sector and hence become financially distressed. This effect is more observable on firms with high levels of indebtedness, low liquidity levels, and with more bank dependency on their financing portfolio. These firms will have to make up cash to meet their short-term obligations through firesales of their illiquid assets that in turn cause a devaluation in the firms' net worth.

(c) Banks observe the contraction of firms' net worth and reduce even more their lending to the real sector to accommodate for the new risk profiles of these firms, as the firms' ability to post collateral in financial transactions reduces and their associated probability of default increases (collateral squeeze).

(d) This negative feedback effect of financial contagion and subsequent loss amplification between the financial and real sectors continues until the system reaches equilibrium.

Our method is general and accepts both negative and positive shocks in the interest rate. The positive shocks in the interest rate are especially helpful to investigate in countries that are experiencing prolonged periods of low interest rates, such as in the USA, whose economy underwent a series of recent increases in the Fed funds rate after a considerable period of expectation of increase by the market. In the other extreme, the negative shocks in the interest rate are more sound to test in economies with consistent and high levels of interest rates, such as in South American countries. The model can identify those economic sectors that would be more or less affected from a change in the monetary policy stance. It can also highlight the sources that are causing the increase or reduction of the sensitiveness to the interest rate shock of each sector. Our model corroborates the fact that high levels of firm indebtedness, low levels

policy shock.

of liquidity, high dependency on external financing, high centrality in the network are factors that increase the sensitiveness of firms to monetary policy shocks.

Figure 1 exhibits the three-layer network that represents our economy, where the top, middle and bottom layers constitute the central bank, financial sector and real sector layers, respectively. Banks and firms can be of any numbers, are allowed to have heterogeneous balance sheet profiles, and can show any interconnection pattern to other members in the economy. A link from A to B in our model embodies financial vulnerability from the former to the latter that can arise either from the asset or the liability side of economic agent A' balance sheet. Financial vulnerability generates co-movements in the balance sheets of linked economic agents and thus is an engine that fuels financial contagion in the economy. The policymaker does not have any vulnerabilities in the system and thus is not exposed to financial contagion nor amplification.

In the financial sector layer, banks with deficit and surplus of liquidity interconnect to satisfy their needs. In the real sector layer, firms also have cross-exposures to meet their liquidity needs or even to match different cashflow seasonality. Every link in the model gives rises to a vulnerability in the asset side of the creditor's balance sheet and a vulnerability in the liability side of the debtor's balance sheet. In the asset side, the creditor economic agent is vulnerable to a loan/credit default and thus represents counterparty risk. For instance, bank 3 lends to bank 1 in the financial sector layer and thus is subject to loan default. In the liability side, the debtor economic agent is vulnerable in the liquidity sense in case the debt is due in the short term and it does not have sufficient cash to meet that financial obligation. For instance, bank 1 has a funding vulnerability to bank 3 in case the exposure is due in the short term and bank 3 does not roll over that debt. Note that links in Figure 1 are bidirectional between banks and firms, but the vulnerability quantification differs with respect to the credit: the vulnerability of the creditor relates to the full loan/credit (outstanding short- and long-term loans/credit), while that of the debtor relates only to the outstanding short-term loan/credit.

Linking the real and financial sector layers, banks and firms also interconnect to boost their profits. On the one side, firms invest in bank bonds that they find profitable, making them susceptible to bond default of that counterparty in the asset side of their balance sheet. For instance, in Fig. 1, firm A bought bonds issued by bank 1 and therefore such investment becomes dependent on the financial soundness of bank 1. In the liability side, firms are vulnerable to credit crunches of the financial sector. A credit crunch may lead firms to readjust their project portfolio and thus can impact their profits. In Fig. 1, firm A is susceptible to a credit crunch of bank 1. On the other side, banks lend credit to firms so that the latter can finance their projects and hence maintain their operational activities toward their customers. Thus, there is a vulnerability in the asset side of banks' balance sheets in view of the loan. In Fig. 1, bank 1 lends to firm A and therefore the former bears the risk of a loan default. In the liability side, banks are susceptible to early redemptions of their bonds that the real sector acquires. In Fig. 1, firm B bought bonds issued by bank 2 and thus the latter is susceptible to early redemption of those bonds.

The financial sector layer communicates with the policymaker layer only unidirectionally. Banks are exposed to variations in the interest rate promoted by the central bank. These changes transmit instantaneously to bank balance sheets due to the daily mark-to-market updates on their trading books (systemic risk-taking). Consequently, bank assets and liabilities vary and therefore bank net worth changes as well. Therefore, this monetary policy instrument gives rise to a financial vulnerability that banks must monitor. In our model, policy interest rate shocks hit first the financial sector and only then are transmitted to the real sector in the form of credit crunches or expansions.

2.2 Microfoundations of the model

The model has two phases: (i) the systemic risk-taking component, which is characterized by an external shock that changes the net worth of banks and (ii) the financial contagion and amplification, which is an after-effect of the first component, characterized by successive credit crunches/expansions to the real sector (amplification) as well as negative spill over effects in the interbank and interfirm markets (contagion). The execution of both components is independent. The output of the systemic risk-taking component gives us an estimate of what extent the net worth of each bank reduces or increases in view of an interest rate shock. The financial contagion and amplification component is then served with this information as input to estimate the short-term sensitiveness of each firm and bank in the model. We detail the two components in

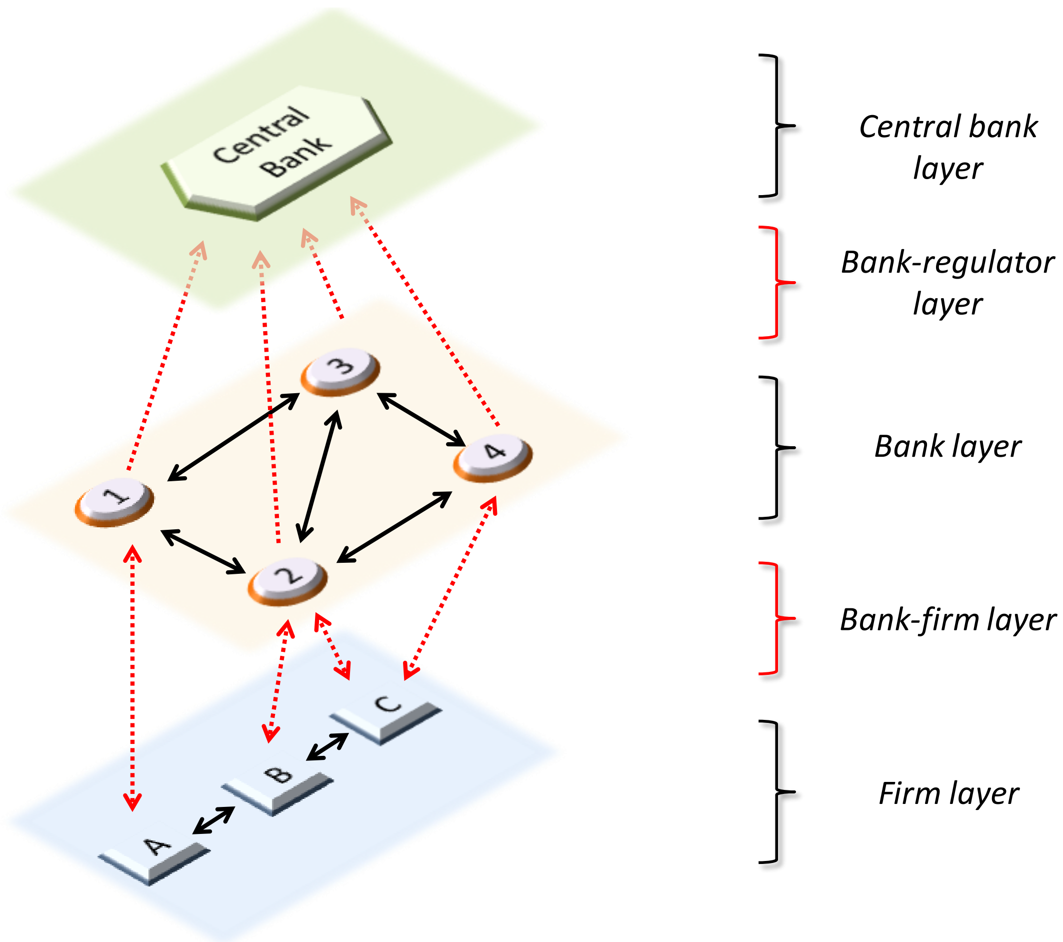


Figure 1: *A multilayer financial network with three layers: bank (circle), firm (square), and central bank (diamond) layers. The central bank regulates changes in the interest rates that in turn impact banks' trading books and hence their net worth. Banks interconnect in the interbank market through borrowing and lending relationships. Firms interconnect in the trade network through credit operations. Banks grant loans to firms and also invest in firm securities. We represent intralayer links with continuous arrowed lines and interlayer links that engine the financial accelerator and regulates bank sensitivity to policy interest rate changes with dashed arrowed lines.*

the following.

2.2.1 The systemic risk-taking component

This component models the short-term sensitivity of banks' net worth to interest rate variations. We consider that the net worth immediate varies as a consequence of daily marking-to-market of assets and liabilities in the trading book that are attached to the interest rate. To capture a comprehensive view of the systemic risk-taking of banks to interest-rate sensitive instruments, we consider variations of the net exposure[11] in twelve vertices of the term structure of the interest rate, each of which corresponding to: 1 day, 1 month, 2 months, 3 months, 6

[11]The net exposure in each of the vertices corresponds to the amount of marked-to-market assets minus the market-to-market liabilities that are attached to the interest rate.

months, 1 year, 2 years, 3 years, 4 years, 5 years, 10 years, and 30 years.

We assume that an interest rate shock causes an immediate change of the term structure of the interest rate. Figure 2 exemplifies a potential reshaping of the term structure for a positive interest rate shock. For each bank i and vertex v in the term structure, we evaluate the new fair value of the stressed net exposure $r_i^{\text{stressed}}(v)$ as follows:

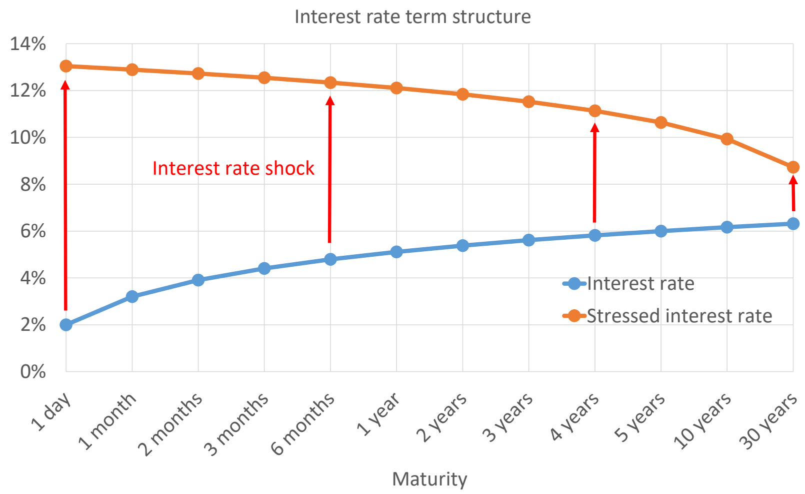


Figure 2: *Example of an interest rate term structure curve (yield curve) before and after a shock (stressed) in the policy interest rate.*

$$r_i^{\text{stressed}}(v) = \frac{r_i^{\text{original}}(v)\left(1 + i_{\text{original}}\right)^v}{\left(1 + i_{\text{stressed}}\right)^v}, \tag{1}$$

in which $r_i^{\text{original}}(v)$ is the original net exposure value (in present value) of bank i that matures in v days, i_{original} is the original interest rate before the shock, and i_{stressed} is the stressed interest rate after the shock. If $i_{\text{stressed}} > i_{\text{original}}$, then the new net exposure value in absolute terms is smaller than the original value. In this situation, when the assets surpasses the liabilities value, i.e., when $r_i^{\text{stressed}}(v) > 0$, the bank incurs losses and its corresponding net worth reduces. When the liabilities value is larger than the assets value, i.e., when $r_i^{\text{stressed}}(v) < 0$, then the bank profits and its net worth increases.

We compute the total gains or losses that bank i is subject to due to the interest rate shock in the trading book by summing the net exposure variations over all vertices in the term structure of the interest rate, i.e.:

$$\Delta r_i = \sum_{v \in \mathscr{V}} \frac{r_i^{\text{original}}(v) \left(1 + i_{\text{original}}\right)^v}{\left(1 + i_{\text{stressed}}\right)^v} - r_i^{\text{original}}(v), \tag{2}$$

in which $\mathscr{V}$ stands for the set of vertices as illustrated in Fig. 2.

Since variations on the trading book must be immediately reflected on the net worth of bank i due to daily mark to marketing, we assume that the net worth of bank i varies by Δr_i. This is the initial shock we use as input to the next phase of our framework.

In this work, we consider that interest rate shocks perfectly shift upwards or downwards the original curve. However, it is worth considering that monetary policy shocks may have different impacts on the term structure of interest rates, such as the curve inversion depicted in Fig. 2. The overall effects of these shocks in terms of potential losses that banks may incur depend not only on the initial shock to the interest rate but also on the change in the term structure of interest rates. If there is a positive monetary policy shock, and the slope increases, then banks that have longer duration in their credit portfolios will suffer higher losses than banks that have shorter duration.

There are different ways in which a stress test scenario for the term structure may be used to perform studies on how monetary policy shocks may impact systemic risk. We can use an econometric model such as the Diebold and Li (2006) to estimate the term structure of interest rates (see Vicente and Tabak (2008) for a discussion on the implementation of Diebold and Li (2006)'s model for Brazil). The estimation can help calculate the potential effects that monetary policy shocks may have on the term structure. Depending on the slope and curvature of the term structure shocks to the interest rate may have different impacts on the term structure, which will have varied effects on the estimation of potential losses that banks may incur.

2.2.2 The financial contagion and amplification component

In this section, we review the microfoundations of Silva et al. (2017a)'s model. We treat banks and firms indistinctively as economic agents. After applying the initial shock on the banks' net worth through changes in the interest rate (systemic risk-taking component), we remove the central bank in this next step because: (i) it is not exposed to any economic agents;

hence, it is insensitive to negative spill over effects, (ii) it cannot default and hence is unable to amplify shocks if we assume that the government is invulnerable in the short term, and (iii) we are dealing with the very short-term consequences of the policy interest rate shock, in such a way that we can assume that the policy interest rate remains fixed in this financial contagion process. Putting these facts together, the central bank is an exogenous entity in the model once the shock is applied to the economy. Therefore, we only focus on understanding the dynamics of the banks' and firms' net worth.

Although our model consists of a single-period economy, we represent the shock propagation process as a dynamic system that may take several iterations before converging. Since our model does not have a time component, because it captures the immediate effect of an external shock, the model is only suitable to estimating the very short-term systemic risk consequences of that event.

For mathematical convenience, we assume that $t = 0$ represents the economy prior to the shock, where t indexes the current iteration of the dynamic system. At $t = 1$, each bank i suffers an interest rate shock promoted by the policymaker according to (2). The way banks internalize this shock varies according to their systemic risk-taking behavior discussed in the previous section. The dynamic system takes as input this shock and therefore iterates from $t = 1$ onwards. At $t > 1$, this shock further propagates in the financial network in the form of successive deterioration of creditors' balance sheets and losses due to firesales. Since economic agents hold positive equities, the shock dissipates as it spill overs along the financial network. Therefore, for a sufficiently large t, the shock settles down and the economic agents' balance sheets reach equilibrium.

To evaluate the potential systemic risk to which the economy is subject by virtue of the interest rate shock, we inspect the portion of net worth that is lost by each economic agent. The larger is this loss, the more fragile the system becomes and therefore the higher is the implied systemic risk. We discriminate the amount that is lost due to the systemic risk-taking and the financial contagion & amplification components. In this way, we can assess the importance of each of these components from a systemic risk viewpoint.

The balance sheet of economic agent i at iteration t consists of three elements:

1. *Assets*: we subdivide the economic agent i's assets at time t, $\mathbf{A}_i(t)$, as assets inside the financial network $\mathbf{A}_i^{(\text{in})}(t)$, which include investments in banks and firms, and external assets $\mathbf{A}_i^{(\text{out})}(t)$, which encompass liquid assets (cash) as well as illiquid assets (such as vehicles and properties). Therefore, $\mathbf{A}_i(t) = \mathbf{A}_i^{(\text{in})}(t) + \mathbf{A}_i^{(\text{out})}(t)$ and $\mathbf{A}_i(t) > 0$.

2. *Liabilities*: we subdivide liabilities of economic agent i at time t, $\mathbf{L}_i(t)$, as inside-network short-term liabilities $\mathbf{L}_i^{(\text{in-st})}(t)$, inside-network long-term liabilities $\mathbf{L}_i^{(\text{in-lt})}(t)$, and outside-network liabilities $\mathbf{L}_i^{(\text{out})}(t)$. Thus, $\mathbf{L}_i(t) = \mathbf{L}_i^{(\text{in-st})}(t) + \mathbf{L}_i^{(\text{in-lt})}(t) + \mathbf{L}_i^{(\text{out})}(t)$ and $\mathbf{L}_i(t) > 0$.

3. *Equities or net worth*: they embody the economic agent's residual value once all liabilities are properly settled, such that $\mathbf{E}_i(t) = \mathbf{A}_i(t) - \mathbf{L}_i(t)$. When $\mathbf{E}_i(t) = 0$, we say that economic agent has defaulted at time t. If $\mathbf{E}_i > 0$, then economic agent i is active. Though equities can achieve negative values by the fundamental accounting equation, our model assumes that economic agents that reach $\mathbf{E}_i(t) = 0$ are immediately put into liquidation and hence are removed from the contagion process, in such a way that $\mathbf{E}_i(t)$ remains at zero in the short run.

Overall equation: We model two risk sources that can reduce economic agent i's net worth: the counterparty and the funding risks. To identify these sources, first consider the differential version of the fundamental accounting equation:

$$\begin{aligned}\Delta\mathbf{E}_i(t) &= \Delta\mathbf{A}_i(t) - \Delta\mathbf{L}_i(t) \\ &= \left[\Delta\mathbf{A}_i^{(\text{in})}(t) + \Delta\mathbf{A}_i^{(\text{out})}(t)\right] - \Delta\mathbf{L}_i(t),\end{aligned} \tag{3}$$

in which we make explicit variations of assets that are inside and outside the financial network. The net worth of economic agent i can reduce in view of (i) direct impacts on its inside-network assets and (ii) indirect impacts on its outside-network assets. Hence, we rewrite the previous equation as:

$$\Delta \mathbf{E}_i(t) = \Delta \mathbf{A}_i^{(\text{in})}(t) + \left[\Delta \mathbf{A}_i^{(\text{out})}(t) - \Delta \mathbf{L}_i(t)\right]$$
$$= \Delta \mathbf{E}_i^{(\text{ct})}(t) + \Delta \mathbf{E}_i^{(\text{f})}(t) \tag{4}$$

in which $\Delta \mathbf{E}_i^{(\text{ct})}(t) = \Delta \mathbf{A}_i^{(\text{in})}(t)$ and $\Delta \mathbf{E}_i^{(\text{f})} = \Delta \mathbf{A}_i^{(\text{out})}(t) - \Delta \mathbf{L}_i(t)$ indicate potential losses due to counterparty risk and funding risk, respectively.

Losses due to counterparty risk: Losses due to counterparty risk arise because economic agents internalize in their balance sheets changes in the debtors' creditworthiness due to fluctuations in the default probability.

This repricing mechanism only assumes that economic agents locally monitor their debtors, i.e., their direct neighbors in the network, to mitigate risk. This is consistent with the fact that (i) apart from the local knowledge of the neighbors (creditors or debtors), the network topology is unknown from the viewpoint of each economic agent and (ii) information asymmetry increases as a function of the (shortest) distance of two economic agents in the network. In particular, economic agents have relatively strong incentives to monitor direct neighbors, while this behavior significantly decreases for neighbors of neighbors and so forth.

We use the following assumption to model how economic agents price inside-network investments:

Assumption 1. *Economic agents reprice down investments solely based on the net worth variation (creditworthiness) of debtors in a linear fashion.*[12]

Using Assumption 1. we assume that creditor i reprices down such investment using a linear decaying function on debtor j's net worth, i.e.:

$$\mathbf{A}_{ij}^{(\text{in})}(t+1) = \begin{cases} \mathbf{A}_{ij}^{(\text{in})}(t)\frac{\mathbf{E}_j(t)}{\mathbf{E}_j(t-1)}, \text{if } j \in \mathscr{A}(t) \\ 0, \text{if } j \notin \mathscr{A}(t) \end{cases} \tag{5}$$

[12] Bardoscia et al. (2015) also use a linear decaying function to simulate a similar investment repricing mechanism.

in which $\mathbf{A}_{ij}^{(\text{in})}(t)$ represents investment value of creditor i in borrower j at iteration t, $\mathbf{E}_j(t)$ is the net worth of j at iteration t, and $\mathscr{A}(t) = \{i \in \mathscr{S} : \mathbf{E}_i(t) > 0\}$ is the set of economic agents that are still active at iteration t, where $\mathscr{S}$ is the set of all economic agents in the economy. We assume that economic agent i reprices the investment $\mathbf{A}_{ij}^{(\text{in})}$ at iteration $t+1$ according to the latest momentum of debtor j's net worth, i.e., $\mathbf{E}_j(t-1)$ and $\mathbf{E}_j(t)$. If debtor j suffers a downfall in its equities, then $\frac{\mathbf{E}_j(t)}{\mathbf{E}_j(t-1)} < 1$, such that $\mathbf{A}_{ij}^{(\text{in})}(t+1) < \mathbf{A}_{ij}^{(\text{in})}(t)$.

Under that assumption, Silva et al. (2017a) demonstrate that losses due to counterparty risk of economic agent i is:

$$\Delta\mathbf{E}_i^{(\text{ct})}(t+1) = \sum_{j \in \mathscr{A}(t-1)} \frac{\mathbf{A}_{ij}^{(\text{in})}(0)}{\mathbf{E}_j(0)} \left[\mathbf{E}_j(t) - \mathbf{E}_j(t-1)\right] \tag{6}$$

in which $\mathbf{A}_{ij}^{(\text{in})}(0)$ and $\mathbf{E}_j(0)$ are exogenous variables representing initial exposure of i to j and the net worth of j, respectively.

Losses due to funding risk: We assume that economic agents perform precautionary liquidity hoarding as they approach insolvency. The hoarding is performed by not rolling over outstanding short-term credit to debtor neighbors in the network (credit crunch). We measure the distance to insolvency by looking at how far from zero the stressed net worth of an economic agent is. To link the extent of the credit crunch and the distance to insolvency, we use the following assumption in our model.

Assumption 2. *The extent of liquidity hoarding linear relates to how close one is to insolvency.*

Generally, if $\mathbf{L}_{ij}^{(\text{in-st})}$ is the outstanding short-term liability of i toward j, then the potential cash outflow in the short term of i to j can range from 0 to $\mathbf{L}_{ij}^{(\text{in-st})}$. Due to Assumption 2, if economic agent j is undistressed, then it fully rolls over the credit to i and no liquidity exposures arise in the short term. In contrast, if j defaults, then it does not roll over any credit and consequently i must pay back all the debt in the short term.

In view of that, we can express the liquidity exposure of i to j as $\alpha_{ij}\mathbf{L}_{ij}^{(\text{in-st})} \in [0, \mathbf{L}_{ij}^{(\text{in-st})}]$, in which $\alpha_{ij} \in [0,1]$ captures the idiosyncrasies between i and j that can either exacerbate or attenuate the consequences of a credit crunch of j on i's financial health. Such term depends on:

- The liquidity conditions of debtor i and creditor j. The more liquid the creditor j is, the less likely it is to restrain credit to its counterparties. In addition, the more liquid the debtor i is, the less affected it will be from a credit crunch of creditor j. For example, if i is liquid enough to withstand the credit restriction, then $\alpha_{ij} = 0$, such that there are no liquidity exposures and therefore no funding risk of i to j.

- The ability of economic agent i to replace the funding counterparty j by another one. The more substitutable j is to i, the less affected i will be from a credit crunch of j.

To estimate losses due to funding risk, we first simplify (4) as follows:

$$\begin{aligned}
\Delta\mathbf{E}_i^{(\mathrm{f})}(t+1) &= \Delta\mathbf{A}_i^{(\mathrm{out})}(t+1) - \Delta\mathbf{L}_i(t+1) \\
&= \Delta\mathbf{A}_i^{(\mathrm{out})}(t+1) \\
&= \Delta\mathbf{A}_i^{(\mathrm{out\text{-}liq})}(t+1) + \mathbf{A}_i^{(\mathrm{out\text{-}illiq})}(t+1) \\
&= \Delta\mathbf{A}_i^{(\mathrm{out\text{-}illiq})}(t+1).
\end{aligned} \tag{7}$$

In the first transition, we use the fact that economic agent i always registers liabilities with their face values, regardless of the financial state of their creditors. In this way, $\mathbf{L}_i(t+1) = \mathbf{L}_i(t)$ because the network links do not change in the model, such that $\Delta\mathbf{L}_i(t+1) = 0, \forall t \geq 0$. In the second transition, we decompose the outside-network assets in terms of their liquidity, in which $\mathbf{A}_i^{(\mathrm{out\text{-}liq})}(t+1)$ and $\mathbf{A}_i^{(\mathrm{out\text{-}illiq})}(t+1)$ denote the liquid and illiquid outside-network assets, respectively. The last transition accounts for the fact that only illiquid outside-network assets are subject to losses.

Equation (7) states that losses due to funding risk occur in view of negative variations of illiquid outside-network assets. This risk component comes into play when economic agent i has to firesale illiquid assets to liquidate its short-term liabilities, thus incurring losses.

The extent of these losses relates to the healthiness of the direct neighbors of i. If they are under increasing distress, they will hoard liquidity and hence will apply a credit crunch to

i in view of Assumption 2. The influence of each neighbor j on i's potential net worth loss is estimated by $\alpha_{ij}\mathbf{L}_{ij}^{(\text{in-st})}$. Then, the losses in illiquid outside-network assets of i vary as a function of the net worth or equities of its creditors j, i.e.:

$$\begin{aligned}\Delta\mathbf{E}_i^{(\text{f})}(t+1) &= \Delta\mathbf{A}_i^{(\text{out-illiq})}(t+1)\\ &= \sum_{j\in\mathscr{A}(t-1)} \alpha_{ij}\mathbf{L}_{ij}^{(\text{in-st})}(t)\left[\frac{\mathbf{E}_j(t)-\mathbf{E}_j(t-1)}{\mathbf{E}_j(t-1)}\right].\end{aligned} \tag{8}$$

But $\mathbf{L}_{ij}^{(\text{in-st})}(t)$ varies linearly accordingly to Assumption 2, such that it follows the same functional form as in (5). Therefore, Equation (8) simplifies to:

$$\Delta\mathbf{E}_i^{(\text{f})}(t+1) = \sum_{j\in\mathscr{A}(t-1)} \frac{\alpha_{ij}\mathbf{L}_{ij}^{(\text{in-st})}(0)}{\mathbf{E}_j(0)}\left[\mathbf{E}_j(t)-\mathbf{E}_j(t-1)\right], \tag{9}$$

in which $\mathbf{L}_{ij}^{(\text{in-st})}(0)$ is the initial short-term liabilities of i to j that is exogenous to the model.

Abstract shock propagation dynamic: Joining both risk sources, Silva et al. (2017a) demonstrate that the total loss of net worth of economic agent i is:

$$\mathbf{s}_i(t+1) = \min\left[1, \mathbf{s}_i(t) + \sum_{j\in\mathscr{S}} \mathbf{V}_{ij}(\text{AS})\Delta\mathbf{s}_j(t) + \mathbf{V}_{ij}(\text{LS})\Delta\mathbf{s}_j(t)\right]. \tag{10}$$

in which $\mathbf{s}_i(t)$ represents the financial stress of economic agents that we evaluate as:

$$\mathbf{s}_i(t) = \frac{\mathbf{E}_i(0)-\mathbf{E}_i(t)}{\mathbf{E}_i(0)}, \tag{11}$$

and $\mathbf{V}(\text{AS})$ and $\mathbf{V}(\text{LS})$ are the vulnerability matrices that numerically translate how financial contagion spills over and impacts economic agents from their asset and liability sides, respectively. These matrices are exogenous to the model and are computed as follows:

$$\mathbf{V}_{ij}(\mathrm{AS}) = \frac{\mathbf{A}^{(\mathrm{in})}_{ij}(0)}{\mathbf{E}_i(0)}, \tag{12}$$

$$\mathbf{V}_{ij}(\mathrm{LS}) = \frac{\alpha_{ij}\mathbf{L}^{(\text{in-st})}_{ij}(0)}{\mathbf{E}_i(0)}, \tag{13}$$

In our framework, we monitor how financial stress of economic agents in (11) increase as shocks propagate across the network. Note that the numerator in (11), $\mathbf{E}_i(0) - \mathbf{E}_i(t)$, quantifies the losses of economic agent i up to iteration t. If economic agent i has not suffered any losses, then $\mathbf{s}_i(t) = 0$. If economic agent is in default, then $\mathbf{s}_i(t) = 1$. In-between values represent partial financial distress. Due to the min[.] operator in (10), this implies $\mathbf{s}_i(t) \in [0, 1]$.

Systemic risk estimation: The systemic risk of a monetary policy shock in the very short term is composed of two terms: (i) the systemic risk due to systemic risk-taking and (ii) the systemic risk due to financial contagion and amplification. We use the financial stress variable (see (11)) to proxy the financial soundness of economic agents, because it numerically supplies the distance to insolvency of economic agents. As systemic risk is a system-wide measure, the idea is to aggregate the financial stress levels of all economic agents using a suitable linear combination.

Assume that the shock propagation dynamic settles down and thus Equation (10) converges for a sufficiently large $t = t_c \gg 1$ after the economy experiences an external shock.

Then, we compute the systemic risk SR of the monetary policy shock using the following expression:

$$SR = \sum_{i \in \mathscr{S}} \mathbf{s}_i(t_c)\nu_i, \tag{14}$$

in which ν_i denotes the economic importance of economic agent i to the overall economy. We proxy the economic importance as the size of the economic agents. To decompose the systemic risk into the systemic risk-taking and financial contagion & amplification components, we manipulate (14) as follows:

$$SR = \sum_{i \in \mathscr{S}} \mathbf{s}_i(1) v_i + \sum_{i \in \mathscr{S}} \left(\mathbf{s}_i(t_c) - \mathbf{s}_i(1)\right) v_i,$$
$$= SR_{\text{risk-taking}} + SR_{\text{contagion}} \tag{15}$$

in which $SR_{\text{risk-taking}} = \sum_{i \in \mathscr{S}} \mathbf{s}_i(1) v_i$ and $SR_{\text{contagion}} = \sum_{i \in \mathscr{S}} \left(\mathbf{s}_i(t_c) - \mathbf{s}_i(1)\right) v_i$. Observe that the systemic risk due to the systemic risk-taking component is evaluated only at $t = 1$, which is the instant that we apply the exogenous monetary policy shock. The systemic risk due to financial contagion and amplification is the additional system-wide financial stress caused by the negative spill-overs to the economy, after removing the influence of the systemic risk-taking component.

2.3 Model definition

In this section, we extend Silva et al. (2017a)'s model to account for monetary policy shocks by tying both the systemic risk-taking and financial contagion & amplification components into a single procedure. For that, to define the vulnerabilities in (12) and (13), we need to explicitly open up the abstract set $\mathscr{S}$ of economic agents into the disjoint sets $\mathscr{B}$ and $\mathscr{F}$, which indicate the set of banks and firms, respectively, such that $\mathscr{S} = \mathscr{B} \bigcup \mathscr{F}$. We also divide the economic agents' stress levels vector $\mathbf{s}(t) \in \mathscr{S} \times 1$ (see (11)) as $\mathbf{b}(t) \in \mathscr{B} \times 1$ and $\mathbf{f}(t) \in \mathscr{F} \times 1$, which represent the stress levels of banks and firms, respectively.

We redefine (10) in terms of stress levels of banks and firms. For that, we first divide inside-network assets $\mathbf{A}_{ij}^{(\text{in})}$ as follows:

- If $i \in \mathscr{B}$ and $j \in \mathscr{B}$, then $\mathbf{A}_{ij}^{(\text{in})} = \mathbf{A}_{ij}^{(\text{bank-bank})}$ is an interbank loan.
- If $i \in \mathscr{B}$ and $j \in \mathscr{F}$, then $\mathbf{A}_{ij}^{(\text{in})} = \mathbf{A}_{ij}^{(\text{bank-firm})}$ represents credit banks grant to firms.
- If $i \in \mathscr{F}$ and $j \in \mathscr{B}$, then $\mathbf{A}_{ij}^{(\text{in})} = \mathbf{A}_{ij}^{(\text{firm-bank})}$ indicates investments of firms in bonds issued by banks.
- If $i \in \mathscr{F}$ and $j \in \mathscr{F}$, then $\mathbf{A}_{ij}^{(\text{in})} = \mathbf{A}_{ij}^{(\text{firm-firm})}$ supplies purchases on credit that the supplier firm grants to the customer firm.

At $t = 0$, all banks and firms are undistressed, i.e., $\mathbf{b}_i(0) = \mathbf{f}_k(0) = 0$, $\forall i \in \mathscr{B}$ and $k \in \mathscr{F}$. At $t = 1$, we set the stress levels of banks and firms according to:

$$\mathbf{b}_i(1) = \min\left[1, -\beta_i\right], \tag{16}$$

$$\mathbf{f}_k(1) = 0, \tag{17}$$

$\forall i \in \mathscr{B}$ and $k \in \mathscr{F}$. The coefficient $\beta_i \in \mathbb{R}$ denotes the net worth variation with respect to initial net worth endowment of bank i that occurs in view of the interest rate shock. We compute this value as follows:

$$\beta_i = \frac{\Delta r_i}{\mathbf{e}_i}, \tag{18}$$

in which Δr_i is the total net worth variation in view of the interest rate shock, which we evaluate in accordance with (2) and $\mathbf{e}_i$ is the initial endowment or net worth of bank i.

For instance, when $\beta_i = 0.10$ ($\beta_i = -0.10$), then bank i gains (loses) 10% of its initial net worth as a consequence of the interest rate shock. In general, if bank i is better off after the shock, then $\beta_i > 0$, implying $\mathbf{b}_i(1) < 0$ (negative stress level).[13] If bank i is worse off after the shock, then $\beta_i < 0$, resulting in $\mathbf{b}_i(1) > 0$ (positive stress level). If bank i is insensitive to the interest rate shock, then $\beta_i = 0$, yielding $\mathbf{b}_i(1) = 0$. When $\mathbf{b}_i > 0$, bank i becomes financially distressed and therefore applies a credit crunch to the real sector. When $\mathbf{b}_i < 0$, it expands credit to firms. Note that firms are always insensitive to the initial monetary policy shock. They are affected via the bank lending channel to the real sector via credit reductions or expansions in later iterations.

For $t > 1$, we use (10) to model how the monetary policy shock spills over to other banks and firms. We specialize the equations to account for the existence of banks and firms. By

[13]For instance, this would happen whenever the policymaker rises the interest level rate and a bank has a trading book mainly composed of mark-to-market liabilities. In this configuration, the value of the bank's trading book in the liability side would decrease more than that in the asset side, such that the bank would profit and thus would become more capitalized.

inspection, we can verify that the abstract model in (10) is equivalent to the following set of equations:

$$\mathbf{b}_i(t+1) = \min\left[1, \mathbf{b}_i(t) + \sum_{j\in\mathscr{B}} \mathbf{V}_{ij}^{(\text{bank-bank})}\Delta\mathbf{b}_j(t) + \sum_{u\in\mathscr{F}} \mathbf{V}_{iu}^{(\text{bank-firm})}\Delta\mathbf{f}_u(t)\right], \tag{19}$$

$$\mathbf{f}_k(t+1) = \min\left[1, \mathbf{f}_k(t) + \sum_{u\in\mathscr{F}} \mathbf{V}_{ku}^{(\text{firm-firm})}\Delta\mathbf{f}_u(t) + \sum_{j\in\mathscr{B}} \mathbf{V}_{kj}^{(\text{firm-bank})}\Delta\mathbf{b}_j(t)\right], \tag{20}$$

in which we divide the vulnerability matrices $\mathbf{V}(\text{AS})$ and $\mathbf{V}(\text{LS})$ in (10) as follows:

$$\mathbf{V}_{ij}^{(\text{bank-bank})} = \mathbf{V}_{ij}^{(\text{bank-bank})}(\text{AS}) + \mathbf{V}_{ij}^{(\text{bank-bank})}(\text{LS}), \tag{21}$$

$$\mathbf{V}_{ku}^{(\text{firm-firm})} = \mathbf{V}_{ku}^{(\text{firm-firm})}(\text{AS}) + \mathbf{V}_{ku}^{(\text{firm-firm})}(\text{LS}), \tag{22}$$

$$\mathbf{V}_{iu}^{(\text{bank-firm})} = \mathbf{V}_{iu}^{(\text{bank-firm})}(\text{AS}) + \mathbf{V}_{iu}^{(\text{bank-firm})}(\text{LS}), \tag{23}$$

$$\mathbf{V}_{kj}^{(\text{firm-bank})} = \mathbf{V}_{kj}^{(\text{firm-bank})}(\text{AS}) + \mathbf{V}_{kj}^{(\text{firm-bank})}(\text{LS}). \tag{24}$$

$\forall i, j \in \mathscr{B}$ and $k, u \in \mathscr{F}$. The idea is to define the matrices (21)–(24) using the functional forms in (12) and (13). Apart from the term $\mathbf{E}(0)$, which is the net worth of banks or firms, we simply need to suitably define the term $\mathbf{A}^{(\text{in})}$ in (12) and the terms α and $\mathbf{L}^{(\text{in-st})}$ in (13) in view of our application.

Terms $\mathbf{A}^{(\text{in})}$ and $\mathbf{L}^{(\text{in-st})}$: Table 1 summarizes how we define $\mathbf{A}^{(\text{in})}$ and $\mathbf{L}^{(\text{in-st})}$.

Table 1: *Sources of vulnerabilities in the asset and liability sides of banks' and firms' balance sheets.*

Creditor	**Debtor**	**Creditor-side vulnerability**		
		Notation	**Asset side (investment)**	**Liability side (funding)**
Firm k	Bank j	$\mathbf{V}_{kj}^{(\text{firm-bank})}$	Bank bonds $\mathbf{A}_{kj}^{(\text{firm-bank})}$	Bank credit crunch of outstanding short-term debt $\mathbf{L}_{kj}^{(\text{in-st})}$
Bank i	Firm u	$\mathbf{V}_{iu}^{(\text{bank-firm})}$	Bank loan $\mathbf{A}_{iu}^{(\text{bank-firm})}$	Early redemption of bank bonds $\mathbf{L}_{iu}^{(\text{in-st})}$
Firm k	Firm u	$\mathbf{V}_{ku}^{(\text{firm-firm})}$	Purchase on credit $\mathbf{A}_{ku}^{(\text{firm-firm})}$	Early redemption of firm securities $\mathbf{L}_{ku}^{(\text{in-st})}$
Bank i	Bank j	$\mathbf{V}_{ij}^{(\text{bank-bank})}$	Interbank loan $\mathbf{A}_{ij}^{(\text{bank-bank})}$	Interbank credit crunch of outstanding short-term $\mathbf{L}_{ij}^{(\text{in-st})}$

Term α_{kj}: This coefficient measures to what extent credit crunches of j would affect the net worth of k and is evaluated as:

$$\alpha_{kj} = \phi_k \phi_j \left[1 - \rho_{kj}\right] \tag{25}$$

$\forall k \in \mathscr{F}$ and $j \in \mathscr{B}$. The coefficients ϕ_k and ϕ_j indicate the level of illiquidity of firm k and bank j, and $\rho_{kj} \in [0,1]$ is a proxy for firm k's ability to replace bank j by another bank. Therefore, the expression $\left[1 - \rho_{kj}\right]$ gives us a sense of the inability of firm k to replace bank j by another counterparty in its funding portfolio.

We first discuss how to compute the inability of firms to switch between banks. Equation (25) considers that the more difficult it is to replace the funding counterparty j, the more firm k will suffer if bank j restrains credit. When bank j is perfectly substitutable, then $\rho_{kj}^{(\text{firm})} = 1$ such that no losses due to funding risk arise. When bank j is singular and cannot be substituted, then $\rho_{kj}^{(\text{firm})} = 0$ such that losses due to funding risk become proportional to the short-term loan that firm k owes to bank j (see (13)).

We calibrate the firms' ability to substitute banks in (25) as a product of two components:

$$\rho_{kj} = [1 - \lambda_k]\left[1 - \mathbf{RL}_{kj}\right], \tag{26}$$

in which $\lambda_k \in [0,1]$ represents firm k's dependency on bank financing and $\mathbf{RL}_{kj}$ stands for its relationship lending history with bank j, which we compute as follows:

$$\lambda_k = \frac{\text{bank debt}_k}{\text{debt}_k + \text{equity}_k}, \tag{27}$$

$$\mathbf{RL}_{kj}(T) = \frac{\sum_{t \in \mathscr{T}} e^{-(T-t)} \mathbf{A}_{jk}^{(\text{bank-firm})}(T-t)}{\sum_{j \in \mathscr{B}} \sum_{t \in \mathscr{T}} e^{-(T-t)} \mathbf{A}_{jk}^{(\text{bank-firm})}(T-t)}. \tag{28}$$

In (27), the term bank $\text{debt}_k = \sum_{j \in \mathscr{B}} \mathbf{A}_{jk}^{(\text{bank-firm})}$ is the total bank debt of firm k, $\text{equity}_k =$

$\mathbf{E}_k(0)$ is the total equities that firm k issues to shareholders, and debt_k represents the total external financing of firm k, which includes bank debt, issued private debt securities, and accounts payables. In (28), the term $\mathscr{T} = \{T, T-1, T-2, \ldots, 0\}$ is a set containing the previous time references and $\mathbf{A}_{jk}^{(\text{bank-firm})}(T-t)$ stands for the amount bank j lent to firm k at the instant $T-t$.

We compute the illiquidity ratio of economic agent k in (25) as follows:

$$\phi_k = \max\left(0, \frac{\text{liabilities}_k^{(\text{short-term})}}{\text{assets}_k^{(\text{liquid})}} - 1\right), \tag{29}$$

in which $\text{liabilities}_k^{(\text{short-term})}$ and $\text{assets}_k^{(\text{liquid})}$ represent the short-term liabilities and liquid assets of economic agent k.

3 Data

We collect and process several unique Brazilian databases with supervisory and accounting data, including the Brazilian credit register that holds millions of credit operations of the banking sector to firms and households in Brazil.[14] We extract quarterly information from December 2013 through September 2016. In the next sections, we discuss how we build the bank-bank (interbank) and bank-firm networks. Due to data unavailability, we consider the network topology of the firm-firm network as an empty graph.

3.1 Financial sector network

We consider all types of unsecured financial instruments registered in the Central Bank of Brazil. Due to domestic regulatory norms, financial institutions must register and report all securities and credit operations, which reinforce the data representativeness and quality. Among examples of financial instruments, we highlight credit, capital, foreign exchange operations and money markets. The money market comprises operations with public and private securities.

Most of the secured lending is through re-purchase agreements with very short maturities

[14] The collection and manipulation of the data were conducted exclusively by the staff of the Central Bank of Brazil.

that are collateralized with Brazilian federal bonds (94 % of total secured lending). Most of the unsecured lending comes from interfinancial deposits (20%), financial bills and debentures (11%), repos issued by the borrower financial conglomerate (7%), and interbank credit (7%). Since the great majority of secured lending has as collateral federal bonds, which in turn are very liquid, if a debtor defaults, creditors can sell off the bonds with no losses even in the very short term. Therefore, we remove secured lending for systemic risk purposes as they do not have counterparty risk.

These operations are registered and controlled by different custodian institutions, which raises the complexity of gathering, pre-processing, and matching the data across different systems. Among the custodian institutions, we extract data from the Cetip[15], which holds operations with private securities, the SCR[16], which registers credit-based operations, and the BM&FBOVESPA[17], which records swaps and options operations.

We consider financial exposures among different financial conglomerates or individual FIs that do not belong to conglomerates. In Brazil, financial conglomerates must account for all the counterparty risk of its branches and subsidiaries. Therefore, we remove intra-conglomerate exposures in the analysis as they are more related to internal capital markets and less to risky operations. We contemplate all banking institutions in Brazil, encompassing commercial banks, investment banks, development banks, federal savings banks, as well as universal banks. There are, on average, 123 active banking institutions in our sample for the analyzed period. We do not include non-banking institutions, such as credit unions, because their contribution to systemic risk is negligible. [18]

[15]Cetip is a depositary of mainly private fixed income, state and city public securities and other securities representing National Treasury debts. As a central securities depositary, Cetip processes the issue, redemption and custody of securities, as well as, when applicable, the payment of interest and other events related to them. The institutions eligible to participate in Cetip include commercial banks, multiple banks, savings banks, investment banks, development banks, brokerage companies, securities distribution companies, goods and future contracts brokerage companies, leasing companies, institutional investors, non-financial companies (including investment funds and private pension companies) and foreign investors.

[16]Among several other types of legal attributions, SCR (Sistema de Informações de Crédito do Banco Central), which is operated by the Central Bank of Brazil, holds operations and securities with credit characteristics and associated guarantees contracted by FIs.

[17]BM&FBOVESPA is a Brazilian-owned company that was created in 2008 through the integration of the São Paulo Stock Exchange (Bolsa de Valores de São Paulo) and the Brazilian Mercantile & Futures Exchange (Bolsa de Mercadorias e Futuros). As Brazil's main intermediary for capital market transactions the company develops, implements and provides systems for trading equities, equity derivatives, fixed-income securities, federal government bonds, financial derivatives, spot FX and agricultural commodities.

[18]For more details, we refer the reader to Silva et al. (2016), Souza et al. (2016) and Silva et al. (2017b) who

We employ as bank equities the sum of their Tier 1 and Tier 2 capital levels. In addition, we assume that the economic importance of banks is given by their total assets. We use the Liquidity Coverage Ratio (LCR) as defined by the Basel III Committee to represent the liquidity levels of banks.

3.2 Bank-firm network (bank credit to the real sector)

Our model requires several accounting data from firms. Unlike the financial sector in which we have complete information on bank exposures, accounting and supervisory data, most of the firms do not report their balance sheet structures. Therefore, we only employ companies whose shares are traded at the Brazilian stock exchange (BM&FBOVESPA)[19] as of December 31$^{\text{th}}$, 2016, as they report balance sheet data, such as registration data, financial statements, and financial indicators, on a quarterly basis. We use Economatica to extract balance sheet information from these firms.

Table 2 reports the original economic sectors of Economatica. We remove the single firm representing the funds sector in Table 2 due to data inconsistency and firms from the finance and insurance sector because they are owned by banks. We also group the software and data and telecommunication sectors into a macrosector that we term as technology sector. We also create the tertiary sector by joining firms in the trade and transportation service sectors. Due to the very low short-term sensitiveness to monetary policy shocks and for the sake of better readability of our graphs, we also remove the sectors: agriculture and fisheries, electric electron, industrial machine, nonmetallic mineral, “others,” textile, and vehicle and parts. Although firms can coexist with negative equities, such as those facing judicial recovery, we remove them because our model uses equities as the main resource of loss-absorption mechanism.

For each of these firms registered at Economatica, we identify the loans that each bank grant to firms from October 2013 through September 2016 on a quarterly basis. We extract

study the structure and systemic risk issues of the Brazilian interbank market.

[19]BM&FBOVESPA, the main Brazilian stock exchange, manages the organized securities and derivatives markets, providing registration, clearing and settlement services, acting as central counterpart. The Exchange offers a wide range of products and services such as spot FX, equities and fixed-income securities trading, as well as trading in derivatives contracts based among other things on equities, financial securities, indices, rates, commodities and currencies. It lists companies and other issuers, is a securities depository, has a securities lending service and licenses software.

Table 2: Number of firms in the sample for each of the 21 economic sectors in the economy. We only account for firms whose shares are publicly traded in the stock exchange.

Economic sector	Number of firms	Economic sector	Number of firms
Electric Power	45	Electric Electron	7
Finance and Insurance	37	Vehicle and Parts	16
Primary and Fabricated Metal	22	Chemical	11
Transportation Service	20	Telecommunication	12
Other	99	Mining	6
Agriculture and Fisheries	5	Oil and Gas	8
Textile	25	Pulp and Paper	5
Food and Beverage	17	Nonmetallic Mineral	4
Construction	22	Software and Data	5
Trade	19	Funds	1
Industrial Machine	5		
		TOTAL	391

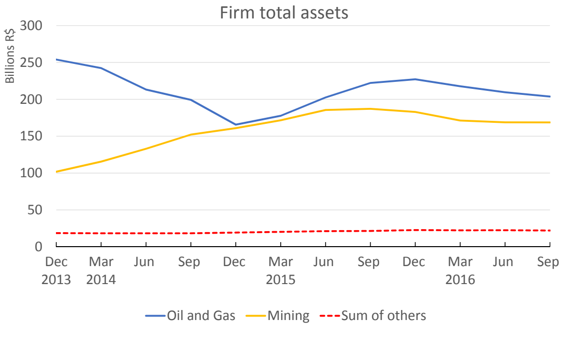
these data from the Central Bank of Brazil's Credit Risk Bureau System (SCR)[20].

Firm-specific characteristics: Figures 3a and 3b portray the average total assets (size) of the economic sectors from December 2013 to September 2016. We separate the oil & gas and mining sectors from the others due to their large comparative size. We see that the average firm size of all sectors, except the oil & gas sector sector, increases until the end of the first semester of 2015. From 2013 to 2016, we highlight the growth of the average firm size in the mining, technology, food & beverage, and electric power, whose average total assets rose by 60%, 55%, 35%, and 65%, respectively.

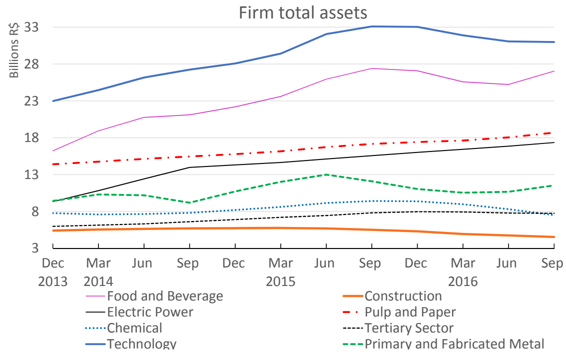
Figures 3c and 3d depict the average net worth (equities) of the economic sectors from December 2013 to September 2016. The large decline in the equities of the oil & gas sector until December 2014 approximately reflects in an one-to-one basis on a similar reduction of its total assets, suggesting that the external financing, such as bank loans, did not increase in this period. After 2014, the average oil & gas sector's total assets increases while its capitalization level remains barely constant, suggesting that external financing and thus the level of indebtedness increases. The average capitalization of the other sectors follows a similar pattern of the total assets of the corresponding sectors.

We now examine the external financing behavior of the economic sectors with respect

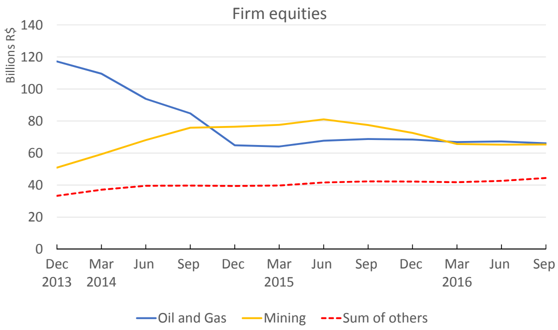
[20] SCR is a very thorough data set which records every single credit operation within the Brazilian financial system worth R$1,000 or above. SCR details the identification of the bank, the client, the loan's time to maturity and the parcel that is overdue, modality of loan, credit origin (earmarked or non-earmarked), interest rate, and risk classification of the operation and of the client.



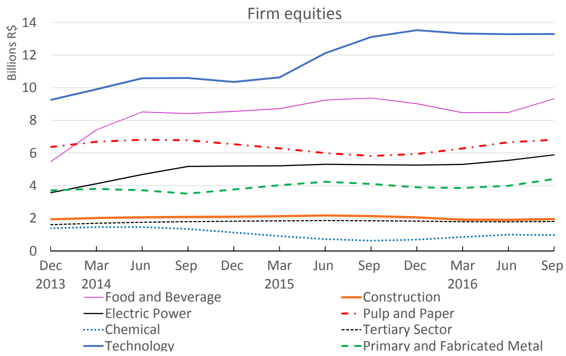
***(a)** Total assets: the largest sectors*



***(b)** Total assets: other sectors*



***(c)** Equities: the largest sectors*



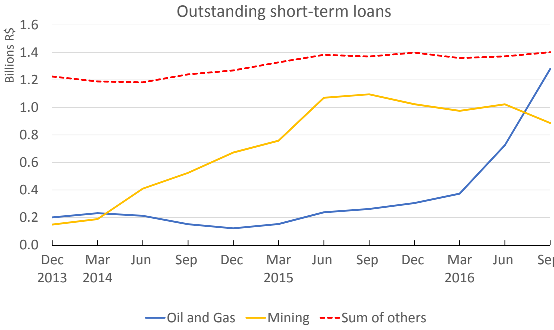
***(d)** Equities: other sectors*

***Figure 3:** Average size (total assets) and net worth (equities) of the Brazilian economic sectors from December 2013 to September 2016. Left panel: (a) Total assets and (c) net worth of the oil & gas sector and the mining sectors against the sum of the corresponding averages of the remaining sectors. Right panel: (b) Total assets and (c) net worth of all economic sectors, except for the oil & gas and the mining sectors.*

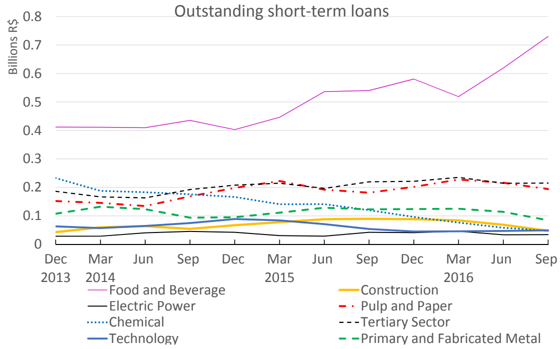
to bank financing. Figures 4a and 4b show the average outstanding bank loans with a time to maturity smaller or equal than 90 days, which we classify as short-term debt.[21] Figures 4c and 4d display the average outstanding bank loans with a time to maturity greater than 90 days, which we classify as long-term debt. We see that the participation of bank financing in the funding portfolio of the oil & gas sector increases from the beginning of 2015. In particular, the level of bank indebtedness shoots up by 50% just in 2015 (Figure 4a and Figure 4c). Thereafter, in 2016, the total outstanding loans slowly decrease while the old loans start to mature, notably those taken in the 2015. We can see this through Fig. 4a, which reports the explosive behavior of the outstanding short-term loans of the oil & gas sector in the beginning of 2016, year in which it skyrocketed by more than 350%. The mining sector takes more and more bank financing from

[21]We suppose that short-term loans are those that are due in the next 90 days rather than the usual assumption of within the current year because our model captures the very short-term consequence of an interest rate shock. In this way, we assume that banks and firms have time to accommodate to funding problems when the loan is due in more than 90 days.

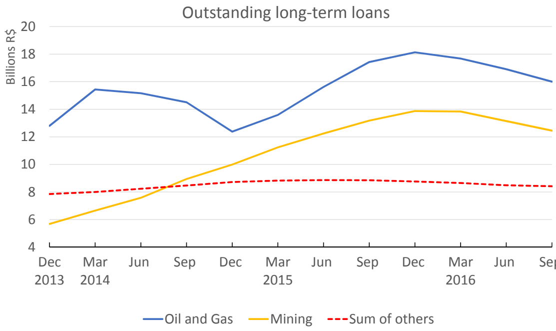
December 2013 until the end of 2015, after which the total outstanding loans start to decrease. In contrast to the oil & gas sector, the behavior of the outstanding short-term loans of the mining sector is more controlled, reaching a maximum in June 2015, after which it slowly declines.



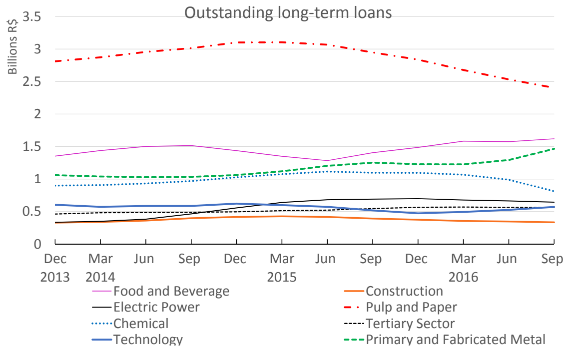
(a) *Outstanding short-term loans: the largest sectors*



(b) *Outstanding short-term loans: other sectors*



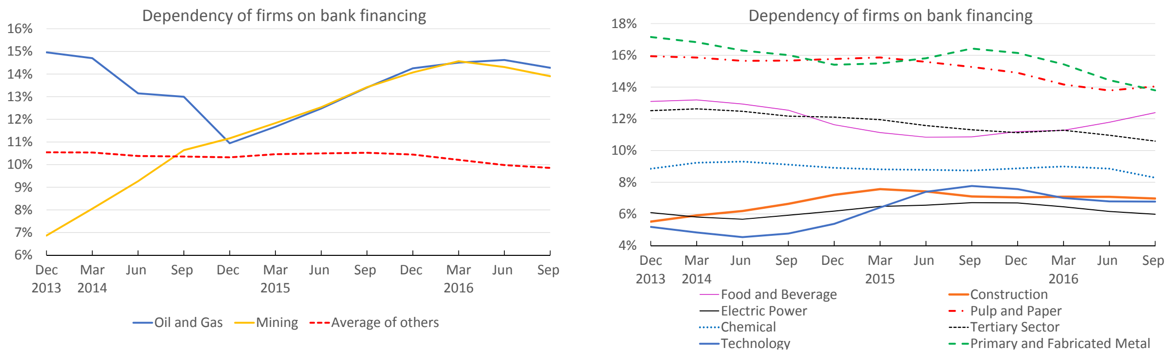
(c) *Outstanding long-term loans: the largest sectors*



(d) *Outstanding long-term loans: other sectors*

Figure 4: *Average outstanding loans of the Brazilian economic sectors over the period ranging from October 2013 to September 2016 in terms of their maturity. Outstanding short-term loan is a loan that is due in the next* 90 *days. Outstanding long-term loan is a loan that is due in more than* 90 *days. Outstanding total loans is the sum of the outstanding short- and long-term loans. The left panel represents the bank loans that are granted to the largest sectors (oil & gas sector and mining sectors) against the sum of the average loans granted to the remaining economic sectors. The right panel portrays bank loans that are granted to all economic sectors, except for the oil & gas and the mining sectors.*

Figures 5a and 5b outline the average dependency of firms in bank financing from December 2013 to September 2016. We highlight the large variation of bank dependency of the mining sector, which doubled from December 2013 to March 2016. After that period, the bank dependency slightly decreased. The oil & gas sector shows a U-shaped pattern: there is a considerable decrease of 26% from December 2013 to the end of 2014 followed by an increase of the same amount until the end of the sample. In regard to the other economic sectors, we observe small changes on the bank dependency levels. Specifically, we see a slight decrease of bank dependency for the primary & fabricated metal, pulp & paper, food & beverage, tertiary sectors; a slight increase of bank dependency for the construction and technology sectors; and a stable bank dependency for the chemical and electric power sectors.



(a) *Dependency of sectors on bank credit: the largest sectors*

(b) *Dependency of sectors on bank credit: other sectors*

Figure 5: *Average dependency of sectors on bank credit over the period ranging from October 2013 to September 2016. (a) Average bank dependency on financing of the oil & gas sector and mining sectors against the average of the remaining economic sectors. (b) Average bank dependency on financing of all economic sectors, except for the oil & gas and the mining sectors.*

Bank-firm network characteristics: We now look at how economic sectors are connected to banks. In our model, banks that endure large losses (gains) in view of changes in interest rate are those that will restrain (expand) more credit to the real sector. Thus, firms that are connected to these banks will be the ones most affected by interest rate changes. Table 3 shows the average share of short-term credit that sectors take from state-owned, domestic private, and foreign private banks. Table 4 depicts the same information but segregating the results in accordance with bank segment: commercial, investment, and development.

The oil & gas sector has predominance of outstanding short-term credit from state-owned banks. With respect to the bank segments, the oil & gas sector seems to be more and more sensitive to potential credit crunches performed by commercial banks. Development banks are the second most importance vulnerability funding source. However, due to the large capitalization of firms in this sector, we expect that the credit crunch impact will be small.

The largest bank creditors in the short term of the mining sector are state-owned and foreign private banks. Likewise the oil & gas sector, the short-term debt of the mining sector is also mostly from commercial banks. Development banks have little participation in the short-term debt.

Table 3: *Share of outstanding short-term credit granted by banks to economic sectors in terms of bank control.*

Sector name	**State-owned**		**Domestic**		**Foreign**	
	Avg	**Std**	**Avg**	**Std**	**Avg**	**Std**
Food and Beverage	0.32	0.02	0.41	0.04	0.27	0.02
Construction	0.38	0.02	0.43	0.03	0.19	0.04
Electric Power	0.41	0.02	0.43	0.03	0.15	0.01
Pulp and Paper	0.37	0.05	0.44	0.04	0.19	0.06
Oil and Gas	0.58	0.09	0.23	0.05	0.19	0.04
Chemical	0.56	0.05	0.31	0.04	0.13	0.05
Primary and Fabricated Metal	0.27	0.01	0.51	0.05	0.22	0.03
Mining	0.42	0.13	0.12	0.06	0.46	0.13
Tertiary Sector	0.28	0.01	0.47	0.04	0.25	0.03
Technology	0.61	0.04	0.35	0.05	0.04	0.01

Table 4: *Share of outstanding short-term credit granted by banks to economic sectors in terms of bank segment.*

Sector name	**Commercial**		**Investment**		**Development**	
	Avg	**Std**	**Avg**	**Std**	**Avg**	**Std**
Food and Beverage	0.94	0.01	0.02	0.01	0.04	0.01
Construction	0.97	0.02	0.03	0.02	0.00	0.00
Electric Power	0.75	0.02	0.02	0.01	0.23	0.02
Pulp and Paper	0.69	0.05	0.02	0.02	0.30	0.04
Oil and Gas	0.53	0.07	0.06	0.06	0.41	0.05
Chemical	0.74	0.06	0.04	0.03	0.22	0.06
Primary and Fabricated Metal	0.93	0.03	0.03	0.02	0.04	0.01
Mining	0.83	0.04	0.01	0.01	0.15	0.03
Tertiary Sector	0.81	0.03	0.07	0.02	0.12	0.01
Technology	0.50	0.09	0.00	0.00	0.49	0.09

4 Results

We divide this section into two parts, each one relating to the systemic risk-taking and the financial contagion and amplification components of the model.

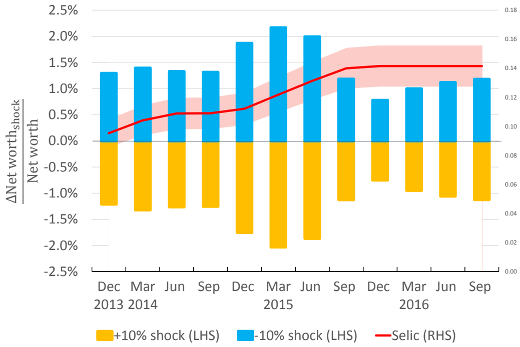
4.1 The systemic risk-taking component

This component regulates how banks' net worth varies as a consequence of an exogenous interest rate shock promoted by the policymaker. Due to mark-to-marketing, banks recognize losses or profits in their trading books in light of changes in the interest rate and therefore their net worth fluctuates accordingly. This variation serves as input for the next phase of the algorithm, in which we estimate the potential financial contagion and amplification that arise due to this interest rate shock.

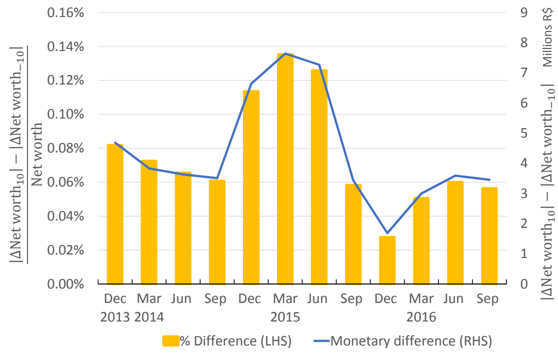
Figure 6a shows the average banks' net worth variation due to a positive and a negative shock of 10% on the nominal interest rate. Therein, we also plot the nominal interest rate curve in Brazil (Selic rate). Our sample only has a monetary policy tightening period that started in Brazil in the beginning of 2013. There are gradual increments of the Selic rate from the beginning of our sample (December 2013) to September 2015, after which the Selic rate stabilized at 14.25%. The higher the interest rate sensitiveness of banks, the larger is their risk-taking behavior and hence they become more exposed to movements in the Selic rate. Note that the first period corresponding to gradual increments of the Selic rate shows the highest components of systemic risk-taking in the financial sector. In 2016, when the Selic rate stabilized at its largest value, the systemic risk-taking component of banks diminished. One possible explanation is that during the period in which Selic rate stabilized, the uncertainty was lower, since the central bank signalized that the interest rate would be the same in the short run. Hence, the variation of the banks' net worth is basically the result of the interest rate shock. However, during the period of monetary policy tightening the variation of banks' net worth could also reflect the uncertainty about the interest rate increment size.

We observe that the systemic risk-taking of banks is not perfectly symmetrical: positive and negative shocks in the interest rate yield slightly different losses or profits. This fact reflects different perceptions of banks with regard to movements on the Selic rate. This can happen, for instance, when banks hedge their positions against variations of the Selic rate on one side only. To check that, Figure 6b plots the absolute difference on the average net worth variation of the financial system due to a $+10\%$ and a -10% interest shock. We also report the asymmetry on the average net worth loss for these two interest rate shocks. Though small, the asymmetry is not constant over time, become more evident in-between September 2014 and June 2015, period in which the Selic rate was being gradually increased by the policymaker.

We now further investigate which banks are more or less sensitive to interest rate shocks



***(a)** Potential net worth loss due to systemic risk-taking*



***(b)** Asymmetry in bank systemic risk-taking*

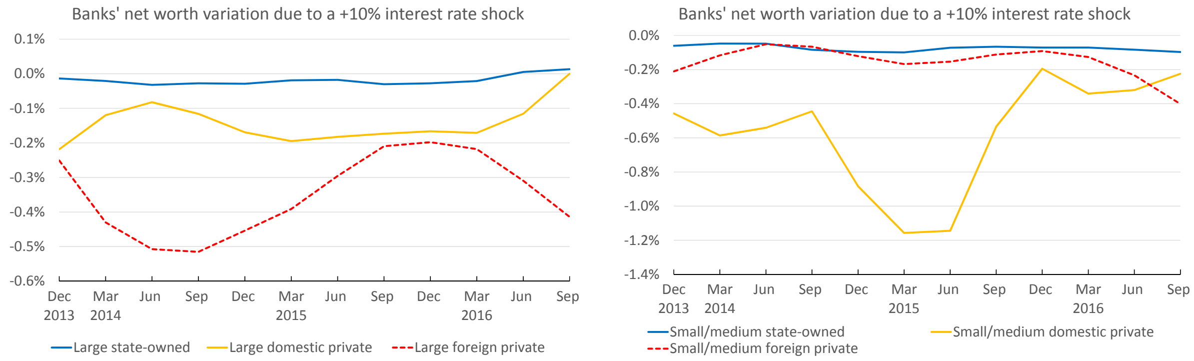
***Figure 6:** Average variation of the banks' net worth as a result of changes on the policy interest rate (systemic risk-taking component). (a) The left-most vertical axis represent the banks' net worth change due to a sudden increase of $+10\%$ (orange bar) and decrease of -10% (blue bar) in the policy interest rate. We also plot the Selic target rate (red curve) in the right-most vertical axis, which is determined by the Central Bank of Brazil. (b) Difference of banks' net worth variation in view of a change of $+10\%$ and -10% in the policy interest rate. The left-most vertical axis indicate $\mid \Delta Net\ Worth_{+10\%} \mid - \mid \Delta Net\ Worth_{-10\%} \mid$ (orange bar), which is the asymmetry in gains/losses that banks face due to the systemic risk-taking component. The right-most vertical axis reports the monetary difference of this asymmetry in terms of banks' net worth (blue curve).*

by segregating our results according to the bank control type—which can be state-owned, domestic private, and foreign private—and bank size[22]—large and small/medium. Figures 7a and 7b portray the average net worth variation that a $+10\%$ interest rate shock causes on large and small/medium banks, respectively.

We see that large state-owned banks are the least sensitive to interest rate shocks. Small/medium state-owned banks also show low sensitiveness to interest rate shocks, but slightly higher than that of large state-owned banks. The reason for the low sensitiveness to interest rate shocks of state-owned banks could be due to their role as main intermediaries of the government for granting earmarked credit. It is well known that the monetary policy has low impact on this type of credit (Bonomo and Martins (2016)), which stands for about 50% of total credit in Brazil.

Small/medium domestic private banks are the most sensitive banks to interest rate shocks. There is a considerable increase of their interest rate sensitiveness during December 2014 to June 2015, showing a relatively large systemic risk-taking component during this period. After June 2015, these banks largely decreased their risk-taking by becoming more resilient to interest rate changes.

[22]We classify banks as large or small/medium as follows. We first construct a cumulative distribution function (CDF) on the banks' total assets and classifies them depending on the region that they fall in the CDF. We consider as large those banks that fall in the 0% to 75% region and as small/medium, otherwise.



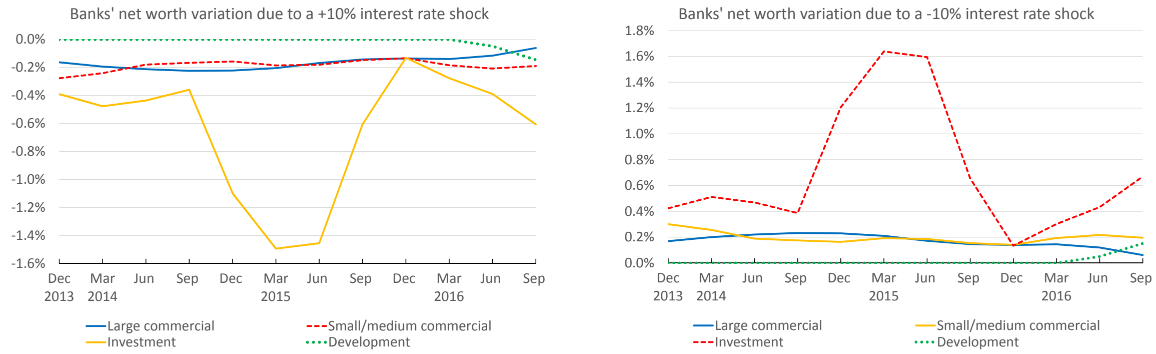
(a) Influence of a $+10\%$ *shock on large banks*

(b) Influence of a $+10\%$ *shock on small/medium banks*

Figure 7: *Short-term consequences on banks' net worth in view of shocks on the policy interest rate (systemic risk-taking component). When the interest rate changes, banks must immediately recognize losses or profits in the trading book portfolios. These figures portray the average net effect on banks' net worth due to these monetary policy shocks, i.e., gains/losses in the asset minus the liability side of their balance sheets. We evaluate the average net effect by bank control: state-owned, domestic private, and foreign private financial institutions.*

Within the category of large banks, foreign private banks are the most sensitive banks to interest rate shocks. While these banks were relatively exposed to interest rate shocks during 2014, these banks' risk sensitiveness decreased during 2015, and again rapidly increased in 2016.

To further understand which types of domestic private banks are more susceptible to changes on the interest rate, Figures 8a and 8b exhibit the average banks' net worth variation due to a $+10\%$ and -10% interest rate shock, respectively, by segregating banks with respect to their main activities: commercial, investment, and development. Due to the large number of banks that fall in this category, we sub-divide commercial banks according to their size. We do not sub-divide the remainder categories to avoid the identification of the banks. We see that the responsible for the large increase of the sensitiveness of banks to interest rate shocks is investment banks. Moreover, they have more perceivable asymmetric profiles with respect to the Selic rate. For instance, an increase of 10% in June 2015 would reduce these banks' net worth by roughly -1.48%, while a decrease would increment their net worth by 1.61%. Development and commercial banks, in contrast, have almost symmetrical profiles with respect to interest rate changes.



***(a)** Influence of a +10% shock on the financial sector*

***(b)** Influence of a −10% shock on the financial sector*

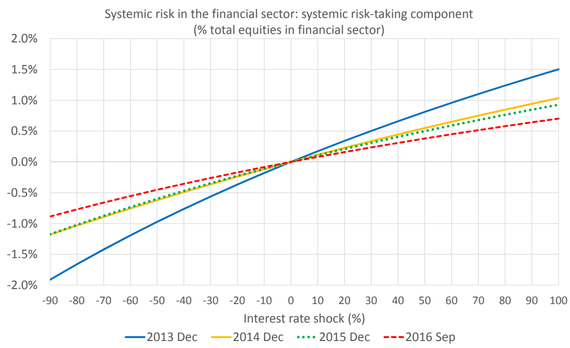
***Figure 8:** Short-term consequences on banks' net worth in view of shocks on the policy interest rate (systemic risk-taking component). We evaluate the average net effect by bank segment and size (when appropriate): large commercial, small/medium commercial, investment, and development financial institutions. We do not segregate investment and development banks by size to prevent identification of banks, as they exist in few numbers in the Brazilian jurisdiction.*

4.2 The financial contagion and amplification component

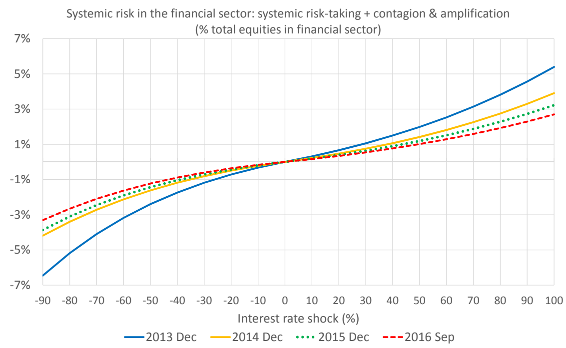
In this section, we analyze the indirect short-term consequences of interest rate shocks in the real and financial sectors. Our analysis is useful for policy decision-making as it permits to identify which economic sectors would be more harmed/benefited in case of a sudden increase or decrease in the interest rate. In our model, the real sector is indirectly affected by banks through credit crunches or expansions. Therefore, sectors that have more outstanding short-term debt, are nearing illiquidity, and have high levels of indebtedness (high leverage and relatively low equities) are likely to be more affected, provided that their creditor banks suffer losses in their trading book portfolio due to the interest rate shock. Conversely, sectors that have large amounts of outstanding loans that are not due in the short term will not be affected by the credit crunch.

In the last section, we investigated the way shocks in the interest rate affected banks' net worth through associated trading book variations. Now, we assume that banks suffered this shock and analyze the posterior short-term consequences using our financial contagion and amplification model.

Systemic risk in the financial sector: We start this section by investigating how changes in the magnitude of interest rate shock can potentially affect the financial health of banks and firms. Our exercise consists in three steps that are performed independently for each time point: (i) vary the interest rate from -90% to 100% of its current rate with steps of 10 percentile points, (ii) calculate the initial impact on banks' net worth using the methodology in Section 2.2.1, and then (iii) evaluate the potential contagion and amplification in the terms of Section 2.2.2. Figure 9a shows the direct impact that banks would suffer in case of variations of the interest rate. We aggregate the financial stress that each bank suffers in response to the interest rate shock to compose the systemic risk due to the systemic risk-taking component (term $SR_{\text{risk-taking}}$ in (15)). Figure 9b portrays the total systemic risk, which corresponds to the components due to the systemic risk-taking and financial contagion and amplification (expression $SR_{\text{risk-taking}} + SR_{\text{contagion}}$ in (15)).



***(a)** Direct impact of interest rate changes*



***(b)** Potential short-term systemic risk in the financial sector*

***Figure 9:** Sensitivity analysis of the magnitude of the interest rate shock with respect to the direct impact on banks' net worth through variations on the trading book value and also the potential indirect impact through financial contagion & amplification. We aggregate the financial stress of banks to compose the systemic risk of the financial sector.*

Though banks' losses or gains in the trading book are positive and linearly related to variations of the interest rate, we observe that non-linearities arise in face of the financial contagion and amplification component. In particular, the systemic risk in the financial sector increases (decreases) linearly with increments (decrements) of the interest rate in the region $[0,40]\%$ ($[-40,0]\%$), point after which such relation becomes non-linear (exponential). The importance of the financial contagion and amplification grows as the interest rate shock gets bigger, suggesting that questions such as "to whom am I connected?" start to matter beside the traditional "am I solvent and liquid enough to withstand expected losses?". Cycles in the network can generate complex spill-over effects and are the main culprits of the non-linearity observed between big interest rate shocks and the implied short-term systemic risk.

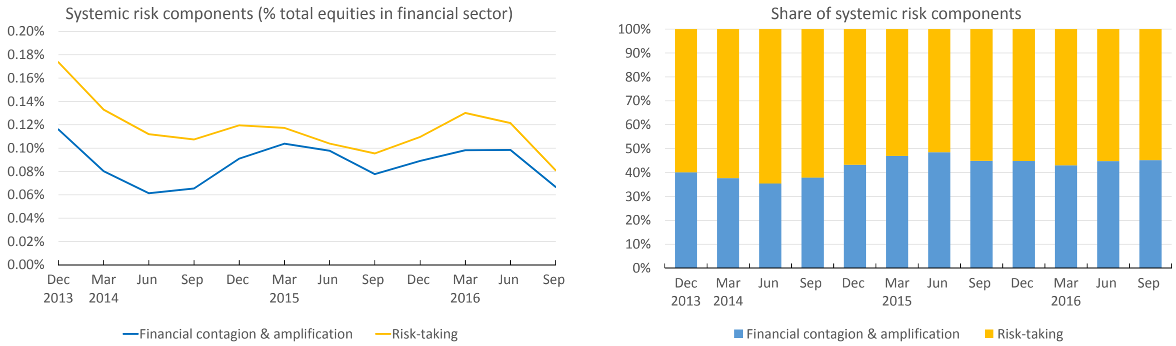
Our finding suggests that big swings in the monetary policy can cause undesirable non-linear consequences on the financial stability of the economy. Thus, it becomes imperative to manage the economic agents' expectations such as to minimize the magnitude of the interest rate shock. Monetary policies with large persistence in the interest rate, as those characterized by interest rate smoothing, are a way to prevent these big swings that enforce the economy into the non-linear regions of systemic risk. In Brazil, for instance, the Central Bank of Brazil maintains relatively large persistence in variations of the interest rate and thus monetary policy shocks have historically remained in the linear region.

In view of this persistence of interest rate variations promoted by the Central Bank of Brazil, for practical reasons, we choose a small interest rate shock to further study in details. Since in Brazil the interest rates have remained historically high, it would be more suitable to understand, for instance, how firms would be affected in case of a sudden decrease of interest rate. In this sense, one could verify whether firms would be equally benefited or rather some sectors would be much better off than others (heterogeneous benefits). Since the sensitiveness of banks to positive and negative variations on the interest rate are nearly symmetrical, we keep our investigation restricted to a positive 10% nominal interest rate shock for didactic purposes.

Figure 10a depicts the short-term systemic risk caused by: (i) the systemic risk-taking component, which directly relates to losses that would occur in case the interest rate shock takes place and (ii) the financial contagion and amplification component, which expresses the potential additional loss that banks would incur in case of materialization of the interest rate shock.

Figure 10b presents the representativeness of each share that composes the total systemic risk of the financial sector. We observe that the systemic risk-taking and financial contagion & amplification components contribute about 60% and 40%, respectively, to the total systemic risk.

To understand which types of banks are more susceptible or sensitive to financial contagion in the short-term due to a $+10\%$ Selic rate shock, we break down the global systemic risk



(a) *Systemic risk in the financial sector*

(b) *Influence of each systemic risk component in the financial sector*

Figure 10: *Systemic risk in the financial sector that is caused by a shock of* $+10\%$ *on the monetary policy rate in the short term. We divide the systemic risk that originates from (i) the systemic risk-taking component, which is the initial impact that banks suffer in their trading books, and (ii) the financial contagion and amplification, which is an after-effect that represents the negative spill-over effects caused by the network. (a) Systemic risk in terms of the total assets in the financial sector. (b) Share of each of the components that influence systemic risk.*

estimates in Fig. 10a in terms of the financial stress that each bank suffers.[23] Table 5 shows the individual short-term financial stress of large and small/medium banks, segregated by bank activity and by bank control.

Table 5: *Financial stress of banks in the short term due to financial contagion and amplification that is caused by a shock of* $+10\%$ *on the monetary policy rate*

	Average (%)	Std. Deviation (%)
Bank type		
Large commercial	0.023	0.005
Small/medium commercial	0.015	0.003
Investment	0.003	0.001
Development	0.045	0.007
Bank control		
Large state-owned	0.055	0.010
Large domestic private	0.009	0.001
Large foreign private	0.005	0.001
Small/medium state-owned	0.003	0.001
Small/medium domestic private	0.009	0.002
Small/medium foreign private	0.007	0.002

We see that large state-owned banks are more susceptible to financial contagion than small/medium banks. We expect this behavior because they intermediate more financial op-

[23]Recall that the systemic risk in the economy is the aggregate of the short-term sensitiveness of all banks, suitably weighted by their economic importance, according to (14). We use the total assets to proxy the economic importance of each bank and firm.

erations, are more central in the network, and therefore shocks can easily reach them via its counterparties (Silva et al. (2016, 2017b)). For a +10% Selic rate shock, the most susceptible banks to financial contagion are large state-owned banks, followed by large domestic private banks, and then large foreign private banks. With regard to bank activity, development banks are the most susceptible banks to financial contagion, followed by commercial, and then investment banks.

One interesting finding is that, while investment banks are the entities that would suffer more from a positive interest rate in the systemic risk-taking component, they would be the least affected through financial contagion and amplification. These entities are not overly exposed to financial contagion because they normally use the interbank market to fund themselves and not to invest. Thus, they have no vulnerability towards other bank counterparties and hence cannot suffer financial contagion. In contrast, they are much more exposed to the systemic risk-taking component mainly due to their risk-related activities. We see an opposing view for state-owned banks: while they are very little affected by the systemic risk-taking component, they would be much more prone to financial contagion and amplification.

Systemic risk in the real sector: In this part, we evaluate the short-term sensitiveness of the real sector to interest rate shocks. Note that our model only captures potential firm financial stress due to credit crunches of the financial sector. For instance, our model does not capture potential losses that firms would be prone to in case they have investments attached to the interest rate. Therefore, one implicit hypothesis of the model is that direct losses/gains due to marked-to-market investments are negligible. In addition, our sample only has firms whose shares are traded at the Brazilian stock exchange market. Though this is a small number of firms, our sample includes most of the largest companies in the Brazil.

Likewise the previous section, Figure 11 displays a sensitivity analysis of the magnitude of the interest rate shock and its indirect impact on the real sector through bank credit crunches. Again we see the existence of regions in which the short-term sensitivity of the real sector is linear with respect to the interest rate shock and other region with a non-linear exponential dependence. However, the slope of the linear region and the exponent of the non-linear region seem to be larger than that of the financial sector. One reason is that firms are much more vulnerable to banks than banks to firms. This is because the capitalization level of banks are higher than of firms.

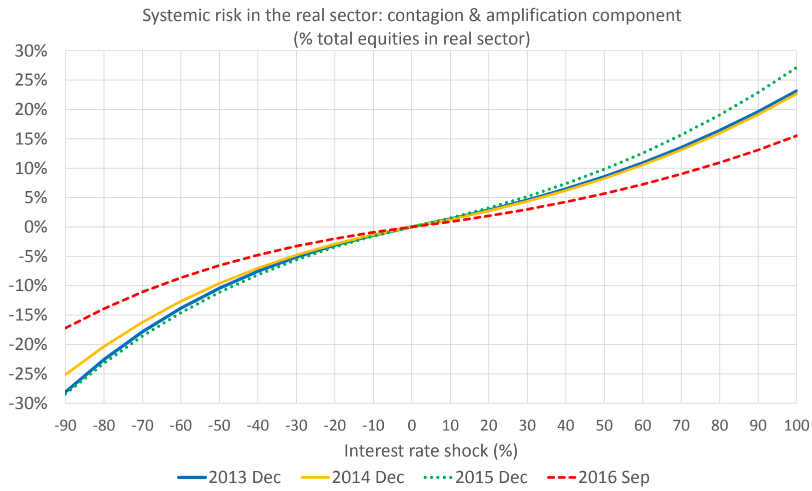
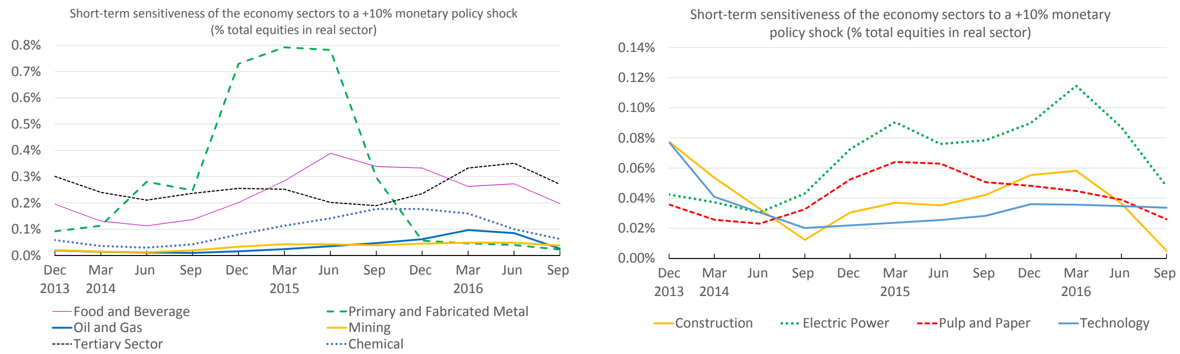


Figure 11: *Sensitivity analysis of the magnitude of the interest rate shock with respect to the indirect impact firms would suffer due to bank credit crunches.*

The remainder of the section focus on the short-term consequences of a small interest rate shock. Figure 12a portrays the short-term sensitiveness of economic sectors to a +10% interest rate shock. For better readability, therein we only plot the curves for the most sensitive sectors—food & beverage, primary & fabricated metal, tertiary, and chemical sectors—as well for the largest sectors in the economy, i.e., the oil & gas and mining sectors. Figure 12b displays the same information but for the least affected sectors: construction, electric power, pulp & paper, and technology sectors. Since the short-term sensitiveness relates to the potential amount of net worth loss of firms, we can give systemic risk intuition for the estimates: the larger the short-term sensitiveness is, the nearer firms will be from insolvency and therefore from a potential default event.

From these systemic risk estimates for the real sector, we can conclude that:

1. *Oil & gas and mining sectors*: they are not sensitive to interest rate shocks in the short-term mainly because: (i) firms are well capitalized (large equities) and therefore have low leverage and indebtedness, reducing their vulnerability to the financial sector; and (ii) though they have large amounts of bank loans, most of them are due in the long term, in such a way that a credit crunch in the present will not put these firms into liquidity or



***(a)** Most sensitive sectors to interest rate shocks + largest economic sectors*

***(b)** Least sensitive sectors to interest rate shocks*

***Figure 12:** Trajectory of the short-term sensitiveness of economic sectors to a* $+10\%$ *interest rate shock from October 2013 to September 2016. (a) Most sensitive sectors: we only plot the estimates for the three most sensitive sectors (food & beverage, tertiary, and chemical sectors) and also for the oil & gas and mining sectors, which are the largest sectors in the Brazilian economy. (b) Least sensitive sectors: we plot sensitive estimates for the electric power, pulp & paper, construction, and technology sectors.*

financing problems.

2. *Primary & fabricated metal sector*: it presents a large short-term sensitiveness to interest rate shocks from the beginning of the sample until the first semester of 2015, period after which it largely declines. This large susceptibility to interest rate shocks in the first semester of 2015 occurs due to the existence of firms with very low equity values, nearing a net capital deficit. In September 2015, some of these very weak firms reached a negative net worth value and therefore were removed from the algorithm (declared as insolvent), because they have no equities to absorb potential losses from financial contagion. As such, only the most capitalized firms remained alive after September 2015, explaining the large decrease in the short-term sensitiveness of this sector to interest rate shocks. Even though this sector only holds small amounts of outstanding short-term bank loans, the relatively large systemic risk estimates corroborate the importance that high capitalization and low levels of indebtedness play as shields against financial contagion.

3. *Tertiary sector*: it constantly remains as one of the most affected sectors to interest rate shocks in the short term. The relatively large estimates occur due to a combination of (i) constant equities of firms in the period, being the second smallest capitalized sector in our sample and (ii) large amounts of outstanding short-term debt, placing as the second

most indebted sector to outstanding short-term bank credit. These two factors together increase the credit crunch influence that firms suffer.

4. *Food & beverage sector*: it is also one of the most susceptible sectors to financial contagion due to credit crunch from the financial sector in case of an interest rate shock. Likewise the tertiary sector, it also presents large amounts of outstanding short-term debt, being placed as the most indebted sector to outstanding short-term bank credit in our sample. However, this sector presents high capitalization, which smoothen the credit crunch influence performed by the financial sector.

5. *Chemical sector:* while this sector shows a clear decreasing pattern with regard to the amount of outstanding short-term loans, which would theoretically decrease their susceptibility to credit crunches, firms in this sector have the lowest capitalization levels among all other sectors in our sample.

The other sectors that appear in Fig. 12b, i.e., the construction, electric power, pulp & paper, and technology sectors, have small short-term sensitiveness to interest rates shock either because they have (i) very small outstanding short-term debt or (ii) high capitalization. Both components soften the influence of the credit crunch that the financial sector applies to the real sector as a consequence of the interest rate shock.

We have seen that the financial sector reacts in asymmetric manner to shocks in the interest rate with respect to their systemic risk-taking component. This phenomenon occurs because some banks may hedge their positions on one side but not the other. Since some banks may gain or lose as a result of the interest rate shock, firms will be affected in heterogenous manners. For instance, banks that had their net worth reduced will perform a credit crunch to the extent of their loss in the trading book. In contrast, banks that had profits in their trading books will expand credit to the real sector. Thus, depending on which type of bank firms are connected, they will improve or deteriorate their net worth. To study how this asymmetry of credit crunches/expansions transmits to the real sector, Figure 13 shows the short-term sensitiveness of all sectors in the economy to a $+10\%$ and -10% interest rate shock in March 2016.

For most sectors, we see that the negative interest rate shock would improve firms' net

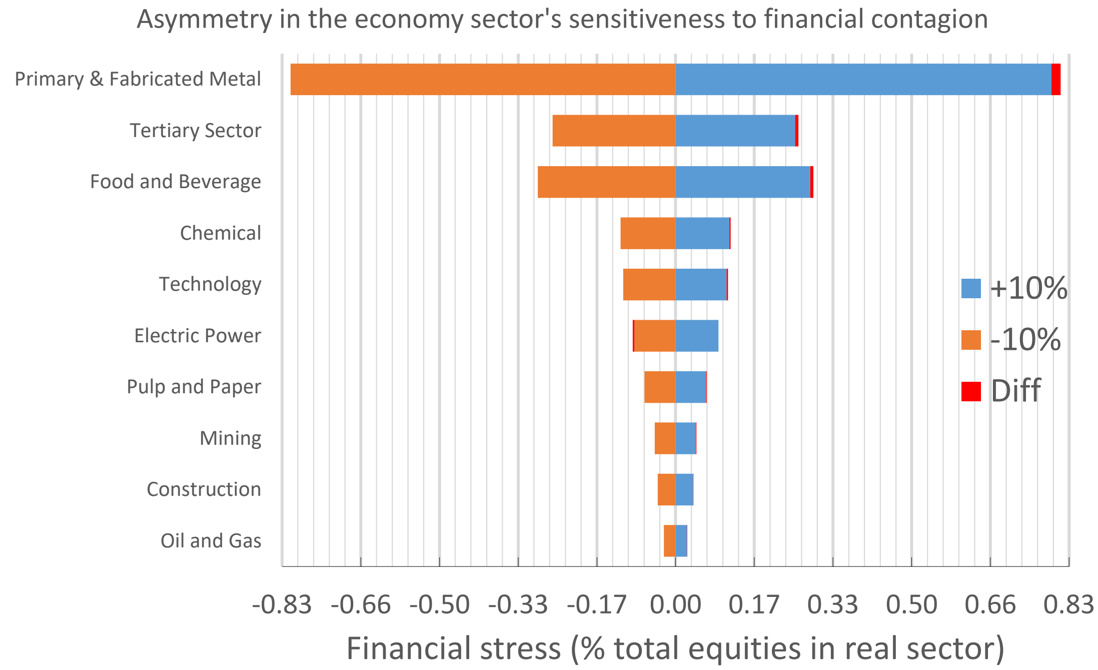


Figure 13: *Asymmetric profiles in the economic sectors' sensitiveness to interest rate shocks in March 2016. We choose this data becomes asymmetry is maximal according to Fig. 6b. We plot the extent of financial contagion that firms are subject to when there is a (a) $+10\%$ (blue bar) and (b) -10% (orange bar) shock in the interest rate. We also draw the quantitative difference (red bar) of this susceptibility in red to highlight the asymmetry.*

worth in the short run more than what a positive interest shock would do in reducing their net worth in absolute terms. For instance, the primary & fabricated metal sector would potentially lose 0.79% of their total net worth in view of a $+10\%$ interest rate shock, but would have its net worth improved by 0.81% in view of a -10% interest rate shock. There is one sector that is exception for that: the electrical power. In the former, for example, a $+10\%$ interest rate shock would cause a corresponding decrease on firms' total net worth of 0.091%, while a -10% interest rate shock would cause an increase of only 0.086% of the total net worth.

Considering the years that comprise our sample, Brazil were on a monetary policy tightening period. Therefore, a positive interest rate shock would convey much less information that a negative shock. Expectations in this period were centered at potential increases of the interest rate, rather than decrements. The observed asymmetry in the way the real sector's net worth is affected follows this reasoning: the increase in the interest rate would cause a harm that would be lower in absolute terms with regard to the improvement firms would have in case a negative interest rate shock of the same magnitude. This is because agents rationalize and internalize in their structure potential future increases in the interest rate.

5 Conclusions

Our results suggest that monetary policy shocks may have adverse short-term impacts on systemic risk through the lending and systemic risk-taking component. We construct a model that allows analyzing these effects, and include contagion and amplification mechanisms to reflect vulnerabilities due to financial interconnections. We also incorporate a feedback engine (financial accelerator) that permits shocks from the real sector to feedback into the financial sector through successive investment downgrades and credit crunches, and so forth.

From a policy perspective, the model is useful to design proper macroprudential policies that aim at mitigating systemic risk as it permits the identification of risk sources in the real sector. In addition, we show that the implementation of monetary policy has short-term effects on financial stability.

We find that monetary policy shocks can have linear or non-linear reflections on the short-term systemic risk in the economy, depending on the shock magnitude. We argue that the non-linearities arise as a result of the interconnection patterns between economic agents. Our results suggest that, as the monetary policy shock gets bigger, questions such as "to whom am I connected?" start to matter beside the traditional "am I solvent and liquid enough to withstand expected losses?". One way to avoid entering the non-linear region is to manage the economic agents' expectations such as to minimize the magnitude of the interest rate shock. Monetary policies with large persistence in the interest rate are a way to prevent these big swings that could enforce the economy into the non-linear regions of systemic risk. In Brazil, for instance, the Central Bank of Brazil maintains relatively large persistence in variations of the interest rate and thus monetary policy shocks have historically remained in the linear region.

We also find an asymmetry in our systemic risk estimates in view of negative or positive monetary policy shocks with the same magnitude. This phenomenon first arises in the systemic risk-taking component of banks due to hedging. Hedging financial operations cause asymmetrical sensitiveness of banks' trading book portfolios and thus their exposure to monetary policy shocks differ in cause of a rise or fall in the interest rate. Second, this phenomenon is further amplified by financial contagion and amplification in the network potentially in a non-linear way. Our study corroborates the fact that hedging can reshape the entire network and either attenuate or amplify systemic risk.

We find that there are specific sectors that are more prone to carry and amplify systemic risk through the economy. The question of whether there should be concentration limits to bank's credit portfolios is worth investigating and further research to exploit this issue is needed. There may be advantages for focused portfolios from a bank's perspective but from a financial stability perspective, it can help in systemic risk buildup.

Positive monetary policy shocks can impact firms through increased cost of funding and also by a decrease in their profit levels (lower consumer demand). While our model indirectly captures the first component through successive credit crunches as a function of the firm creditworthiness, we abstract away from the second risk channel. We do not have information to support how representative is one risk source to another for our model, in a way that our systemic risk indices could be underestimated. In addition, our empirical approach supposes that a monetary policy shock causes the term structure of the interest rate to perfectly shift upwards or downwards. However, monetary policy shocks have a strong effect in mark-to-market assets and liabilities due in the short term, particularly when we deal with its short-term consequences in the economy. Therefore, a more realistic approach would be to pin down the long horizon of the term structure of the interest rate while letting loose the short-term part of the curve. This addition is left as future work.

References

Acemoglu, D., Ozdaglar, A., and Tahbaz-Salehi, A. (2015). Systemic risk and stability in financial networks. *American Economic Review*, 105(2):564–608.

Acharya, V., Engle, R., and Pierret, D. (2014). Testing macroprudential stress tests: the risk of regulatory risk weights. *Journal of Monetary Economics*, 65:36–53.

Ashcraft, A. B. and Campello, M. (2007). Firm balance sheets and monetary policy transmission. *Journal of Monetary Economics*, 54(6):1515–1528.

Bardoscia, M., Battiston, S., Caccioli, F., and Caldarelli, G. (2015). DebtRank: a microscopic foundation for shock propagation. *PLoS ONE*, 10(6):e0130406.

Battiston, S., Farmer, J. D., Flache, A., Garlaschelli, D., Haldane, A. G., Heesterbeek, H., Hommes, C., Jaeger, C., May, R., and Scheffer, M. (2016). Complexity theory and financial regulation. *Science*, 351(6275):818–819.

Battiston, S., Puliga, M., Kaushik, R., Tasca, P., and Caldarelli, G. (2012). DebtRank: too central to fail? Financial networks, the FED and systemic risk. *Scientific reports*, 2:541.

BCBS (2015). Fundamental review of the trading book – interim impact analysis. Basel committee on banking supervision publications, Bank for International Settlements, Basel, Switzerland.

Benoit, S., Colliard, J.-E., Hurlin, C., and Pérignon, C. (2017). Where the risks lie: A survey on systemic risk. *Review of Finance*, 21(1):109.

Bernanke, B. (1983). Nonmonetary effects of the financial crisis in the propagation of the Great Depression. *American Economic Review*, 73:257–276.

Bernanke, B. and Gertler, M. (1989). Agency costs, net worth, and business fluctuations. *American Economic Review*, 79:14–31.

Bernanke, B., Gertler, M., and Gilchrist, S. (1996). The financial accelerator and the flight to quality. *Review of Economics and Statistics*, 78:1–15.

Bernanke, B. S. and Blinder, A. S. (1992). The federal funds rate and the channels of monetary transmission. *American Economic Review*, 82(4):901–921.

Bernanke, B. S. and Gertler, M. (1995). Inside the black box: the credit channel of monetary policy transmission. *Journal of Economic Perspectives*, 9(4):27–48.

Bluhm, M., Faia, E., and Krahnen, J. P. (2014). Monetary policy implementation in an interbank network: Effects on systemic risk. Working Paper Series 46, Research Center SAFE.

Bonomo, M. and Martins, B. (2016). The impact of government-driven loans in the monetary transmission mechanism: what can we learn from firm-level data? Working Paper Series 419, Central Bank of Brazil.

Bruno, V. and Shin, H. S. (2015). Capital flows and the risk-taking channel of monetary policy. *Journal of Monetary Economics*, 71:119–132.

Dell'Ariccia, G., Laeven, L., and Marquez, R. (2014). Real interest rates, leverage, and bank risk-taking. *Journal of Economic Theory*, 149:65–99.

Dell'Ariccia, G. and Marquez, R. (2006). Lending booms and lending standards. *Journal of Finance*, 61(5):2511–2546.

den Haan, W. J., Sumner, S. W., and Yamashiro, G. M. (2007). Bank loan portfolios and the monetary transmission mechanism. *Journal of Monetary Economics*, 54(3):904–924.

Diamond, D. W. and Rajan, R. G. (2012). Illiquid banks, financial stability, and interest rate policy. *Journal of Political Economy*, 120(3):552–642.

Diebold, F. X. and Li, C. (2006). Forecasting the term structure of government bond yields. *Journal of Econometrics*, 130(2):337–364.

Disyatat, P. (2011). The bank lending channel revisited. *Journal of Money, Credit and Banking*, 43(4):711–734.

Eisenberg, L. and Noe, T. H. (2001). Systemic risk in financial systems. *Management Science*, 47(2):236–249.

Elliott, M., Golub, B., and Jackson, M. O. (2014). Financial networks and contagion. *American Economic Review*, 104(10):3115–53.

Eser, F. and Schwaab, B. (2016). Evaluating the impact of unconventional monetary policy measures: empirical evidence from the ECB's securities markets programme. *Journal of Financial Economics*, 119(1):147–167.

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

Georg, C.-P. (2013). The effect of the interbank network structure on contagion and common shocks. *Journal of Banking and Finance*, 37(7):2216–2228.

Hanson, S. G., Kashyap, A. K., and Stein, J. C. (2011). A macroprudential approach to financial regulation. *Journal of Economic Perspectives*, 25(1):3–28.

Hubrich, K. and Tetlow, R. J. (2015). Financial stress and economic dynamics: the transmission of crises. *Journal of Monetary Economics*, 70:100–115.

IMF, BIS, and FSB (2009). Guidance to assess the systemic importance of financial institutions, markets and instruments. Report to the G20 Finance Ministers and Governors. *International Monetary Fund, Bank for International Settlements, and Financial Stability Board.*

Jiménez, G., Ongena, S., Peydró, J.-L., and Saurina, J. (2012). Credit supply and monetary policy: identifying the bank balance-sheet channel with loan applications. *American Economic Review*, 102(5):2301–26.

Jiménez, G., Ongena, S., Peydró, J.-L., and Saurina, J. (2014). Hazardous times for monetary policy: what do twenty-three million bank loans say about the effects of monetary policy on credit risk-taking? *Econometrica*, 82(2):463–505.

Kashyap, A. K. and Stein, J. C. (2000). What do a million observations on banks say about the transmission of monetary policy? *American Economic Review*, 90(3):407–428.

Maddaloni, A. and Peydró, J.-L. (2011). Bank risk-taking, securitization, supervision, and low interest rates: evidence from the Euro-area and the U.S. lending standards. *Review of Financial Studies*, 24(6):2121–2165.

Silva, T. C., Silva, M. A., and Tabak, B. M. (2017a). Systemic risk in financial systems: a feedback approach. Working Paper Series 461, Central Bank of Brazil.

Silva, T. C., Souza, S. R. S., and Tabak, B. M. (2016). Network structure analysis of the Brazilian interbank market. *Emerging Markets Review*, 26:130–152.

Silva, T. C., Souza, S. R. S., and Tabak, B. M. (2017b). Monitoring vulnerability and impact diffusion in financial networks. *Journal of Economic Dynamics and Control*, 76:109–135.

Souza, S. R. S., Silva, T. C., Tabak, B. M., and Guerra, S. M. (2016). Evaluating systemic risk using bank default probabilities in financial networks. *Journal of Economic Dynamics and Control*, 66:54–75.

Stein, J. C. (2012). Monetary policy as financial stability regulation. *Quarterly Journal of Economics*, 127(1):57–95.

Steiner, A. (2014). Reserve accumulation and financial crises: from individual protection to systemic risk. *European Economic Review*, 70:126–144.

Vicente, J. and Tabak, B. M. (2008). Forecasting bond yields in the Brazilian fixed income market. *International Journal of Forecasting*, 24(3):490–497.

BANCO CENTRAL DO BRASIL