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The interaction between monetary and macroprudential policy: should central banks 'lean against the wind' to foster macro-financial stability?

Sebastian Krug

Abstract

The extensive harm caused by the financial crisis raises the question of whether policy-makers could have done more to prevent the build-up of financial imbalances. This paper aims to contribute to the field of regulatory impact assessment by taking up the revived debate on whether central banks should use the interest rate to directly respond to the build-up of financial sector imbalances, i.e. 'lean against the wind' or not. Currently, there is no consensus on whether monetary policy is, in general, able to support the resilience of the financial system or if this task should better be left to the macroprudential approach of financial regulation. The author aims to shed light on this issue by analyzing distinct policy regimes within an agent-based computational macro-model with endogenous money. He finds that policies that make use of their comparative advantage lead to superior outcomes concerning their respective intended objectives. In particular, he shows that 'leaning against the wind' should only serve as first line of defense in the absence of a prudential regulatory regime and that price stability does not necessarily mean financial stability. Moreover, macroprudential regulation as unburdened policy instrument is able to dampen the build-up of financial imbalances by restricting credit to the unsustainable high-leveraged part of the real economy.

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1 Introduction

In a competitive environment, banks' private choices concerning money creation are not socially optimal burdening the economy with externalities and leaving the system vulnerable to financial crises. In this context, the focus should be on "*how to exploit the magic of credit for growth without inciting banks to imprudent lending practices*", as Giannini (2011) puts it, and how to avoid states of the financial system which are macro-economically destructive instead of growth-supportive.

Historically, central banks emerged as institutional counterbalance in order to be in control of the banking sector and to restrict the risk of financial imbalances [Haldane and Qvigstad; Hellwig (2014); Stein (2012); Goodhart (1988)]. But over time, the focus turned more and more from (direct) crisis mitigation towards the current dual mandate since it was generally agreed that inflation represents one of the main sources of financial instability and that achieving price stability would be sufficient to ensure also financial stability [Schwartz (1995)]. The occurrence of the recent financial crisis disabused both practitioners as well as researchers.[1]

In the course of the recent resurgence of interest in the nexus of finance and macroeconomics [Morley (2015)], there are numerous invocations to put such considerations back on the research agenda emphasizing that the focus on inflation bears the potential of omitting other measures of economic stability and sustainable growth [Woodford (2012); Walsh (2014); Borio (2014); Stein (2014); Tarullo (2014); George (2014)]. As a consequence, many central banks face calls to expand their policy goals towards financial stability issues. The corresponding debate is mainly on whether to continue to entirely rely on financial regulation and macroprudential policy instruments to ensure financial stability [Hanson et al. (2011); Criste and Lupu (2014); Tomuleasa (2015)] or to respond directly to financial imbalances through monetary policy.

For the vast majority of central banks around the world, flexible inflation targeting has become the predominant monetary policy regime and proponents argue that financial stability issues can represent a natural extension [Olsen (2015)]. For example, Woodford (2012) states that central banks should implement a policy which is seeking

> *"to deter extreme levels of leverage and of maturity transformation in the financial sector."* Even *"modest changes in short-term rates can have a significant effect on firm's incentives to seek high degrees of leverage or excessively short-term sources of funding. Again, this is something that we need to understand better than we currently do;*

[1] Albeit even prior to the crisis there was some early awareness of the fact that this view is not correct [e.g. Borio (2006); Issing (2003)]. For empirical evidence on the missing positive correlation between price and financial stability, see Blot et al. (2015).

> *acceptance that monetary policy deliberations should take account of the consequences of the policy decision for financial stability will require a sustained research effort, to develop the quantitative models that will be needed as a basis for such a discussion."*

Moreover, R. Bookstaber adds in his speech at the INET conference 2014 that "*we have to embed financial regulation deeply within macroeconomics and in particular monetary policy, the interface between those two is untried territory*". A similar kind of invocation was also made by Mishkin (2011) who states that "*research on the kind of quantitative models needed to analyze this issue should probably be a large part of the agenda for central-bank research staffs in the near term*".

But there are not only arguments in favor of an extended flexible inflation targeting since monetary and financial-stability policy are distinct and separate policies with different objectives and different instruments, as Svensson (2012) argues. Thus, a direct central bank response to, say, credit growth would inevitably suggest a violation of Tinbergen's famous *effective assignment principle* [Tinbergen (1952)], i.e. to assign only one objective to each independent policy instrument which, in turn, implies that policymakers cannot be "the servant of two masters". Therefore, Svensson emphasizes that "*[. . .] the policy rate is not the only available tool, and much better instruments are available for achieving and maintaining financial stability. Monetary policy should be the last line of defense of financial stability, not the first line*". Ignoring the principle of Tinbergen bears the risk of an overreactive monetary policy leading to a highly volatile target rate which might entail destabilizing effects on the primary goals of the central bank. Also Yellen (2014); Giese et al. (2013) argue that using macroprudential policy would be the more effective and direct way while Smets (2014) emphasizes the importance of an appropriate coordination in order to avoid conflicts of interacting policies.

These considerations necessarily raise the question whether the analysis framework usually used by central banks is the right instrument to derive scientific guidance for policy makers. Existing research in this field is yet still dominated by studies using DSGE models as underlying framework for the analysis [Käfer (2014); Chatelain and Ralf (2014); Plosser (2014)]. In this context, Mishkin (2011) states that the underlying linear quadratic framework of pre-crisis theory of optimal monetary policy has a significant shortcoming, i.e. the financial sector does not play a special role for economic fluctuations. This naturally led to a *dichotomy between monetary and financial-stability policy* resulting in a situation in which both are conducted separately.[2] However, Adrian and Shin (2008a,b) argue against "*the common view that monetary policy and policies toward financial stability should be seen separately, they are inseparable*". Moreover, there are some early studies

[2] See Suh (2014) which shows the existence of the dichotomy in a New Keynesian model with credit.

which have argued that the current monetary policy framework could fail to deal with financial instability because it largely ignores the development of variables that are usually linked to financial imbalances, e.g. credit growth or asset prices [Cecchetti et al. (2000); Bordo and Jeanne (2002); Borio and Lowe (2002, 2004)]. For a more recent critique see Gelain et al. (2013) who state that the analysis of the nexus between monetary and macroprudential policy "*requires a realistic economic model that captures the links between asset prices, credit expansion, and real economic activity. Standard DSGE models with fully rational expectations have difficulty producing large swings in [private sector] debt that resemble the patterns observed*" in the data. Also Agénor and Pereira da Silva (2014) choose a simple dynamic macroeconomic model of a bank-dominated financial system for their analysis because it "*provides [. . .] a better starting point to think about monetary policy [. . .] compared to the New Keynesian model [. . .] which by now is largely discredited. The days of studying monetary policy in models without money (and credit) are over [. . .]*".[3]

Although the framework is continuously extended and meanwhile also the banking sector and financial frictions are taken into account,[4] relying entirely on a single kind of model to analyze policy issues might bear the risk of "*backing the wrong horse*".[5] Hence, the new insights gained in the aftermath of the crisis might be a good reason to approach monetary policy analysis within alternative frameworks. Moreover, Bookstaber (2013) strongly argues in favor of agent-based computational economic (ACE) frameworks to do research on financial stability issues.

We contribute to the literature on regulatory impact assessment and the interaction between monetary policy and financial stability in the following way: First, by providing an agent-based macro-model[6] with endogenous money, we contribute to model pluralism in this area. Currently, we are not aware of any comparable studies using an ACE model in this field, except for Popoyan et al. (2017); Alexandre and

[3] See also Disyatat (2010).

[4] Recent examples would be Levine and Lima (2015); Gambacorta and Signoretti (2014); Badarau and Popescu (2015); Rubio and Carrasco-Gallego (2014). For a literature overview on monetary policy and financial stability using DSGE models with financial frictions as framework for the analysis, see Verona et al. (2014); Chatelain and Ralf (2014); Akram and Eitrheim (2008).

[5] Haldane and Qvigstad state that "*Model or epistemological uncertainty can to some extent be neutralized by using a diverse set of approaches. This, again, can avoid the catastrophic policy errors that might result from choosing a single model and it proving wrong. The workhorse macro-economic model, without banks and with little role for risk and asset prices, predictably showed itself completely unable to account for events during the crisis. Use of this singular framework for example, for gauging the output consequences of the crisis would have led policymakers seriously astray. Using a suite of models which emphasized bank, asset prices and risk transmission channels would generated far better forecasting performance through the crisis [. . .]*".

[6] The ACE model is programmed in Scala 2.12.4.

Lima (2017) and somewhat more broadly also Salle et al. (2013b,a) who analyze the credibility of central bank's inflation target announcements.[7] Endogeous money supply here means that the quantity of money is determined endogenously, i.e. as a result of the interactions of factors within the private sector, rather than exogenously (or autonomously) by the central bank. Hence, the central bank is not able to fully control the money supply via the supply of reserves. It can only affect economic activity through incentives related to monetary policy while the provision of reserves is fully flexible according to the real sector's credit demand. This theory is much more suitable to explain the functioning of a modern monetary economy than its neo-classical analogy. For an excellent taxonomy of existing theories of banking that underpins the decision of the authors to explicitly model the endogenous money or also credit creation theory of banking, see Werner (2016).

Second, instead of usually incorporating only single macroprudential policy instruments (e.g. loan-to-value ratio (LTV)), our experiments encompass complete regulatory regimes, i.e. Basel II and Basel III. This enables us to run counterfactual simulations of the model relative to a benchmark scenario which is comparable to the economic environment of the pre-crises period, i.e. a situation with a rather loose regulatory environment (Basel II) and a central bank focusing solely on price and output stability. Based on this benchmark scenario, we then test the impact of either a tightened financial regulation, of various degrees of a central bank's response to financial imbalances and a combination of both. As also done by Gelain et al. (2013), results are considered in terms of the two objectives of both policies, (macro)economic and financial stability, in order to shed light on potential conflicts and crowding-out effects.

Our experiments provide three main findings. First, assigning more than one objective to the monetary policy instrument in order to achieve price, output and financial stability simultaneously, confirms the expected proposition of the Tinbergen principle in the sense that it is not possible to improve financial stability additionally to the traditional goals of monetary policy. The results of our experiments show that after a long phase of deregulation, "leaning against the wind"[8] has a positive impact on price and output stability but affects the fragile financial system only marginally.

[7] Also somewhat related to the research question at hand is the work of Gualdi et al. (2016) who develop a stylized ACE model to explore the efficiency of monetary policy and potential consequences of "unbalanced" decisions made by the central bank. Moreover, Ryoo and Skott (2016) present a model in which the authors test the possibilities to stabilize the economy using monetary policy tools within Keynesian and Harrodian frameworks.

[8] In his speech from 2005 on "Asset price bubbles and monetary policy", Jean-Claude Trichet, former president of the ECB, described the phrase in the following terms: *"The leaning against the wind principle describes a tendency to cautiously raise interest rates even beyond the level necessary to maintain price stability over the short to medium term when a potentially detrimental asset price boom is identified."*.

Moreover, in a system in which banks have to comply with tight prudential requirements, a central banks' additional response to the build-up of financial imbalances does not lead to improved outcomes concerning both macroeconomic and financial stability. In contrast, using prudential regulation as an independent and unburdened policy instrument significantly improves the resilience of the system.

Second, "leaning against the wind" should only serve as a first line of defense in the *absence* of prudential financial regulation. If the activity of the banking sector is already guided by an appropriate regulatory framework, the results are in line with Svensson (2012) who argues that "the policy rate is not the only available tool, and much better instruments are available for achieving and maintaining financial stability. Monetary policy should be the last line of defense of financial stability, not the first line". Macroprudential policy dampens the build-up of financial imbalances and contributes to the resilience of the financial system by restricting credit to the unsustainable high-leveraged part of the real economy. This strengthens the view of opponents who argue that both policies are designed for their specific purpose and that they should be used accordingly.

Third, our results confirm that, in line with Adrian and Shin (2008a,b), both policies are inherently connected and, thus, influence each other which emphasizes that an appropriate coordination is inevitable and that the prevailing dichotomy of the currently used linear quadratic framework may lead to misleading results.

The remainder of the paper is organized as follows: in Section 2, we give an overview of the structure of the underlying ACE model (while a part concerning common macroeconomic stylized facts which are replicated by the model is outsourced to the appendix B) followed by a detailed description of the conducted experiments in Section 3. Section 4 provides a discussion of the results for different monetary policy rules comparing their performance in terms of macroeconomic and financial stability. Section 5 concludes.

2 The Model

2.1 Purpose

The agent-based macroeconomic model presented in the following consists of six types of agents, i.e. households and firms representing the real sector, a central bank, a government and a financial supervisory authority forming the public sector and a set of traditional banks (financial sector). Agents are heterogeneous in their initial endowments of e.g. productivity, amount of employees or clients and interact through a goods, labor and money market in order to follow their own needs, like consuming or making profit. Figure 1 provides an overview of the relationships between types of agents on a monetary level.

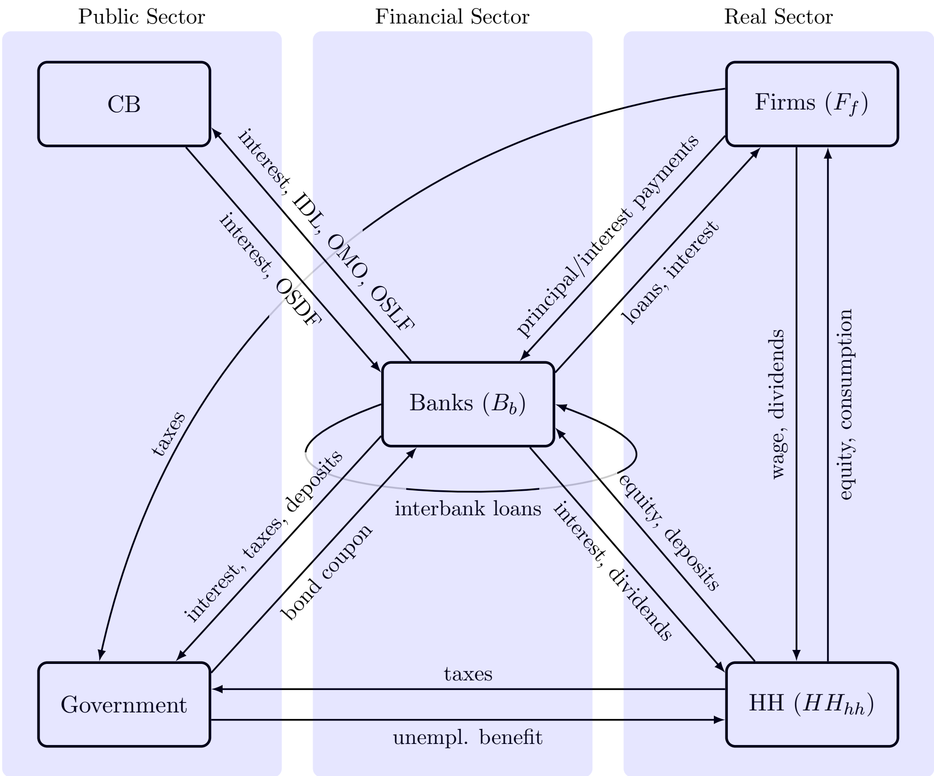


Figure 1: Monetary flows in the model

As a result of the interaction of heterogeneous agents, the model exhibits common macroeconomic stylized facts emerging through the course of the simulation such as endogenous business cycles, GDP growth, unemployment rate fluctuations, balance sheet dynamics, leverage/credit cycles and constraints, bank defaults and financial crises, as well as the need for the public sector to stabilize the economy [Riccetti et al. (2015)] (see also Appendix B).

Since the model should serve as an experimental lab to analyze policies regarding monetary policy and banking regulation, we focus on the monetary system and model it in great detail. Therefore, we adopt as much as possible from the functionality of the real world template provided by the Bank of England's "UK Sterling Monetary Framework" [Bank of England (2014c)]. Here, the CB plays a crucial role since it implements monetary policy as usual in developed countries by setting a target interest rate which directly affects the whole set of existing interest rates, in particular the rates charged on loans to the real sector by means of increased refinancing costs. Through the resulting effect on credit demand, the CB's monetary policy transmits to overall economic activity, i.e. to production and price levels and, thus, to inflation and output. Therefore, the presented model is well suited to analyze the question of whether macro-financial stability issues should be an explicit concern of monetary policy decisions or if it should be better left to macroprudential regulation and banking supervision. The rest of the paragraph describes the fundamental design concepts of the model.

2.2 Design Concepts

The underlying time scheme is divided into ticks (one unit of time) whereas every tick t represents a week. In our model, every month has exactly 4 weeks which leads to an experimental quarter of 12 weeks and an experimental year that consists of only 48 (instead of 52) weeks. This means that variable x_t represents the value of x in tick t while x_{t-12} represents the value of x 12 weeks ago, i.e. the value of the previous quarter.

As stated above, a substantial part of agents' interaction takes place on markets through a matching process. To determine the specific set of matching pairs for a certain action between two agents, i.e. between households and firms on the labor and goods market or between two banks on the interbank market, a pre-selection mechanism is applied to the whole set of agents that generates subsets and, thus, constrains the interaction space in order to meet certain stylized facts. The pre-selection mechanisms as well as the matching mechanism applied to the subsets are randomized.

Concerning the underlying behavioral assumptions, we state that agent's in the model are purely backward looking. They do form expectations on e.g. the inflation rate but these expectations entirely depend on the past development of the inflation rate. Thus, agent's do not have the ability to collect and process massive amounts of data in order to perform (perfect) forecasts that guide their decisions. Moreover, agents also do not use any optimization procedures to follow their needs and to interact in a fully rationale way. Instead, they are boundedly rational and decision making is largely based on rules of thumb and heuristics. Our aim is to model agents that are restricted in their decision-making capabilities but still have to cope with a relative complex world. Furthermore, the current version of the model does not include any learning capabilities of agents, thus, the decision rules do not alter over time. Agents do know their own state variables but not those of other agents.

Concerning the exit and entry of agents, only corporations, i.e. firms and banks can go bankrupt. In such a case of a default of an agent, all its connections to other agents and to the network of claims are resolved appropriately until the agent has, again, a state that equals the state at its initialization. So, the agent-object does not vanish, nor is it deleted but when it re-enters the market after a random amount of time and under certain preconditions it operates like a new firm or bank agent.

Finally, there are no external sources used as input during run-time. The remainder of this section covers the description of the behavior of each type of agent in more detail.

2.3 Sequence of Simulated Economic Activity (Pseudo Code)

In this section, we show the economic activities as they occur during the simulation process. This should impart a rough idea of the functionality of the underlying agent-based macro-model and its consisting parts. The rest of the section describes these parts in more detail. The corresponding source code can be found in Krug (2016). The simulations consist of the following parts:

1. Start economic interaction of settlement period t ($t = 1, \ldots, 3000$)
    - Banks settle their overnight/short-term interbank liabilities (if any)
    - Banks settle their overnight/short-term standing facility liabilities with the CB (if any)
    - Banks set up repos with CB of maintenance period (if new period starts)
2. Real sector activity (planning phase)
    - Reactivation of firms (if any)
    - Firms determine their production target
    - Firms determine their offered wage
    - Firms determine their credit demand (external financing)
    - Firms send credit requests to banks
    - Firms announce vacancies
    - Firms fire employees if they face an overproduction
3. Government pays unemployment benefit to unemployed HH
4. Real sector activity (production phase)
    - Unemployed HH search for a job / firms hire workers in case of a match
    - Firms produce and offer their bundle of goods
    - HH plan and conduct consumption
5. Real/public sector debt obligations
    - Firms pay wages and meet their debt obligations (risk for firm default due to illiquidity)

- Government pays principal/interest on outstanding bonds

6. End of settlement period t
   - Test for firm defaults due to insolvency (annual report)
   - Banks repay intra day liquidity (IDL) to the CB (if any)
   - Banks conduct interbank lending (overnight; if necessary)
   - Banks use standing facility of the CB (if necessary)
   - CB pays interest on reserves
   - Banks determine their profit / pay taxes (if any) / pay dividends to HH (if any)
   - Test for insolvencies of banks (annual report)
   - Government bail out of systemically important banks
7. Monetary policy decisions
   - CB sets target rate and corresponding interest environment
   - CB/Supervisor set regulatory requirements (Basel III accord)

2.4 Start Economic Interaction of Settlement Period

Relationship Bank

The initial bilateral relationships between bank b (with $b = 1,\dots,B$) and real sector agents are assigned randomly, i.e. each household and firm chooses a bank where it places its deposits and requests loans. These relationships do only change in the case of a default of an agent. In the case of a bank default, all clients of the insolvent bank randomly choose a new bank and if a new founded bank enters the market, clients of other banks have a small probability to switch. New firms also choose their banks randomly. The same holds for the ownership relationships since firms and banks are owned by households. Furthermore, we suppose that all economic transactions are conducted by only using scriptural money, i.e. there exist no banknotes (cashless economy).

Public Debt

At the beginning of every simulation of the overdraft economy, the government brings money into the system by issuing bonds ($B_{G,t}$ and $GB_{b,t}$ increase) and selling them to the commercial banks and the central bank (CB) which pay by crediting

Assets	Liabilities
Bank Deposits ($D_{G,t}$)	Public Debt ($B_{G,t}$)
CB Deposits ($D^{CB}_{G,t}$)	Equity ($E_{G,t}$)
Total Assets ($TA_{G,t}$)	

(a) Balance Sheet 1: Example government

Assets	Liabilities
Business Loans ($BL_{b,t}$)	Retail Deposits ($RD_{b,t}$)
Wholesale Loans ($WL_{b,t}$)	Gov. Deposits ($GD_{b,t}$)
Gov. Bonds ($GB_{b,t}$)	Wholesale Liab. ($WO_{b,t}$)
Interest Receiv. ($IR_{b,t}$)	CB Liabilities ($CBL_{b,t}$)
CB Reserves ($R_{b,t}$)	Equity ($E_{b,t}$)
Total Assets ($TA_{b,t}$)	

(b) Balance Sheet 2: Example bank *b*

Figure 2: Balance sheet structure of government and banks

the government's accounts ($D_{G,t}$ and $GD_{b,t}$ increase, see Figure 2).[9] The bonds have a face value of 1000 monetary units and a duration of 5 years. The fix annual coupon orientates at the target rate of the central bank in period t (i^*_t), and lies slightly (15 basis points) above it [Choudhry (2010)]. The present value of each bond is determined by its clean price (neglecting accrued interest) using the standard textbook formula from Bodie et al. (2010)

$$p^{clean}_{k,t} = \frac{\left(\frac{2+i^*_t}{2}\right)^{-n_{k,t}+\frac{\Omega_{k,t}}{\Upsilon_{k,t}}} \cdot FV_{k,t}\left[i^*_t + c_k\left(\left(\frac{2+i^*_t}{2}\right)^{n_{k,t}} - 1\right)\right]}{i^*_t} - \frac{c_k \Omega_{k,t} FV_{k,t}}{2\Upsilon_{k,t}} \quad (1)$$

where $FV_{k,t}$ denotes the face value of bond k in t, c_k the coupon, $n_{k,t}$ the amount of remaining coupon payments at t, $\Omega_{k,t}$ the amount of days since the last coupon payment, and $\Upsilon_{k,t}$ the total days in the coupon period.

The received deposits enable the government to spend and every time it runs out of deposits, it repeats this transaction in order to ensure its financial ability to act [Lavoie (2003)].[10] The issued public debt is tax-financed.

Monetary Framework

The underlying monetary framework of the model follows the post-keynesian theory of endogenous money [see Lavoie (2003) among others], i.e. the amount of money in

[9] This process is part of the endogenous money approach described in Lavoie (2003) where the starting point of economic activity is that the government issues bonds, i.e. the promise to pay back the face value as they mature plus interest over time, meaning that it encumbers itself with (public) debt. In order to be able to act within the payment system, it is in need of deposits. It sells the issued bonds to private banks that grant deposits according to the bonds face value in return. Thus, the transaction creates money since banks do not purchase the bonds with existing funds but by granting deposits to the government. For a dynamic model of the money creation process, see Li et al. (2017).

[10] This leads to the fact that government bonds represent a large part of the banks' assets but this seems to be reasonable in times where the market-based non-traditional banking sector is larger than the traditional retail banking sector, e.g. in the U.S. [Mehrling (2012)].

the system is determined by the investment decisions of real sector agents (demand-driven) instead of the supply of the CB (supply-driven). Thus, we implement a monetary system along the lines of the *UK Sterling Monetary Framework* of the Bank of England (BoE) using it as a template.[11] The orientation seems to be reasonable, since the BoE itself recently attracted attention in the field by implicitly accepting the endogenous money theory in their in-house journal, the *BoE Quarterly Bulletin* [McLeay et al. (2014a,b)].

At the heart of the UK reserve averaging scheme[12] is a *real-time gross settlement* (RTGS) system [Kelsey and Rickenbach (2014); Dent and Dison (2012); Nakajima (2011); Arciero et al. (2009)] which enables the CB to provide liquidity insurance to commercial banks via operational standing facilities (OSF) and, thus, to meet its lender of last resort (LOLR) function. This means that the settlement of a transaction between real sector agents takes place as soon as a payment is submitted into the system (real-time) and that payments can only be settled if the paying bank has enough liquidity to deliver the *full* amount in central bank money (gross settlement, i.e. no netting takes place) [Galbiati and Soramäki (2011)].

Reserve Target and Maintenance Period Since each bank has to pledge a sufficient amount of collateral for the reserves borrowed from the CB,[13] the initial endowment of reserves is efficient when it equals the bank's expected net transaction volume of the settlement day. Hence, each bank chooses an amount of reserves that covers a fraction of its current interest-bearing deposits (i.e. liquidity that customers can potentially transfer to another bank). In our model this fraction is $1/15$ according to Ryan-Collins et al. (2012) who state that this is a usual value for banks within the UK monetary system. The endowment is called *reserve target* ($R^*_{b,t}$) and can be adjusted at the beginning of each maintenance period

$$R^*_{b,t} = \frac{RD_{b,t} + GD_{b,t}}{15} \qquad \text{(see balance sheet 2).} \tag{2}$$

A maintenance period runs from one CB target rate decision to the next and, thus, has a duration of 4 weeks.

[11] A good description can be found in Bank of England (2014c); Ryan-Collins et al. (2012).

[12] Although it was suspended after the recent financial crisis in 2009 and a Quantitative Easing (QE) scheme is prevailing instead, the reserve averaging scheme can be considered as the default scheme implemented in normal times. With respect to the aim of the model, i.e. to evaluate monetary policies contribution to macro-financial stability, a scheme with a comparable setting to the pre-crises period of 2007/2008 seems to be a reasonable choice.

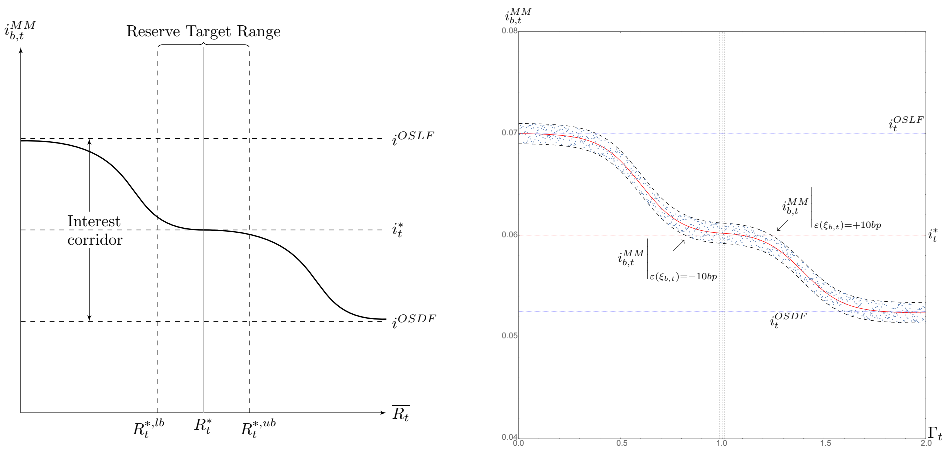
[13] Repos with the CB are conducted according to the international accounting standards, meaning that the bonds pledged as collateral still appear in the balance sheet of the borrower since he still faces the entire economic risk (also the coupon is paid to the borrower although the bonds are placed as collateral) [Choudhry (2010)].

Liquidity Management Unfortunately, banks usually face an unpredictable stream of payments to execute during the settlement day meaning that it is likely for them to end up with an amount of reserves that lies either above (excess reserves) or below $R^*_{b,t}$ (reserve deficit). In order to ensure the proper functioning of the payment system, i.e. to ensure that each bank has enough reserves to conduct the payments of their customers, the CB incentivizes banks to manage their liquidity by only paying interest on the reserve holdings of a bank if its maintenance-period average reserve holdings lie within a narrow 1%-band around $R^*_{b,t}$ (reserve target range). Hence, if a bank has met its reserve target range, it will be credited with the CB's target rate i^*_t against its average balance at the end of each maintenance period. The monetary system provides three liquidity management mechanisms for banks that they can use to compensate deviations from $R^*_{b,t}$ and to adjust their reserve accounts in such a way that they reach their reserve target range (see 3a). The following part describes the three mechanisms of the RTGS system in more detail:

A. *Intraday Liquidity (IDL)*: If a bank needs reserves during the course of the settlement day in order to process a payment of a customer because the transaction volume exceeds its current reserve balances, it can borrow the needed reserves from the CB via extreme short-term (intraday) repos. This intraday liquidity has to be repaid at the beginning of the closing procedure of each settlement day [Bank of England (2014a); Dent and Dison (2012); Ryan-Collins et al. (2012)]. Thus, the provision of IDL ensures that any payment of banks' clients can be settled in real-time and on a gross basis.[14] Note, that the immediate repayment means that the CB does not provide any long-term finance for banks nor will it provide reserves or lend to insolvent banks (bailouts are exclusively conducted by the government). Of course, payments received from other banks can rebuild the reserve balances but more likely is a net in- or outflow of reserves after the settlement of intraday liquidity which requires the usage of further liquidity management mechanisms. Banks now have the opportunity to reallocate reserves through the interbank market or, if this is not possible for some reason, to use the standing facilities and borrow (deposit) the needed funds overnight from (at) the CB.

B. *Interbank Lending*: Concerning the modeling of the interbank lending activity, the difficulty arose from the fact that the theoretical framework provided by the BoE only consists of a graphical representation as shown in Figure 3a, i.e. without any mathematical description in form of a function or the like.

[14] This mechanism implicitly assumes that there is no lack of collateral, which represents the current situation in financial markets. In such a case, the bank would simply securitize some assets to meet the need for collateral.



(a) Corridor System of reserves (theoret.) **(b)** System within the model

Figure 3: Interbank rate, banks' demand for reserves and the interest corridor of the CB [Bank of England (2014c); Ryan-Collins et al. (2012); Winters (2012)]

Therefore, we decided to develop and implement such a formal representation of the interbank interest rate based on the provided logic of the BoE.

Hence, we model the interbank market as a (decentralized) over-the-counter (OTC) market which requires bank b (in need of reserves) to find a counterparty within the set of all other banks willing to lend reserves to b [Afonso and Lagos (2015)]. The conditions for overnight interbank repos are then based on bilateral negotiation about volume and interest charged. Whereas the volume depends on the counterparties current excess reserves, the costs of borrowing reserves on the interbank market $i^{MM}_{b,t}$ faced by bank b depend on three parts:

(a) The first part is the CB's target rate i^*_t since its operating standing facility rates for borrowing reserves from (i^{OSLF}) and depositing reserves at the CB (i^{OSDF}) build a corridor around i^*_t and, thus, determine the overall level of the prevailing interest environment.

(b) The second part is the aggregate amount of current average reserves holdings ($\overline{R_t}$) relative to the aggregate reserve targets (R^*_t), i.e. the current supply of excess reserves on the interbank market (Γ_t):

$$\Gamma_t = \frac{\sum_{b=1}^{B} \overline{R_{b,t}}}{\sum_{b=1}^{B} R^*_{b,t}} = \frac{\overline{R_t}}{R^*_t}. \tag{3}$$

Γ_t serves as a measure of how far the current aggregate average reserves ($\overline{R_t}$) are away from the aggregate reserve target (R^*_t) or, put differently, the current potential for reserve reallocation. If there are a lot of excess reserves and the potential for reallocating reserves among banks is high, the interest on interbank loans ($i_{b,t}^{MM}$) is lower, i.e. close to the deposit facility rate of the CB (i^{OSDF}). If reserves are scarce, $i_{b,t}^{MM}$ is higher, i.e. closer to the rate charged for borrowing reserves overnight from the CB (lending facility rate i^{OSLF}).[15]

(c) The third part is a small risk premium that depends on bank b's current financial soundness $\varepsilon(\xi_{b,t})$. It is measured by its debt-to-equity ratio $\xi_{b,t}$ and it ranges between -10 and +10 basis points. Hence, realizations of $i_{b,t}^{MM}$ fall within the scope of a small band around $i_{b,t}^{MM}\big|_{\varepsilon(\xi_{b,t})=0}$ (Figure 3b shows this exemplary for $i_t^* = 0.06$ and $\Gamma_t \in (0,2)$).

Thus, the prevailing incentive scheme shown in Figure 3a/3b leads to an individual interbank rate for bank b of

$$\begin{aligned} i_{b,t}^{MM}(i_t^*, \Gamma_t, \xi_{b,t}) = \\ & \left\{ g(\Gamma_t)\left[\sigma_1 - \sigma_2 \cdot \tanh\left(\varphi\Gamma_t - \frac{3}{2}\varphi\right)\right] \right. \\ & \left. \quad + \left(1 - g(\Gamma_t)\right)\left[\sigma_3 - \sigma_4 \cdot \tanh\left(\varphi\Gamma_t - \frac{\varphi}{2}\right)\right] \right\} \\ & \quad - (0.06 - i_t^*) + \varepsilon(\xi_{b,t}) \end{aligned} \tag{4}$$

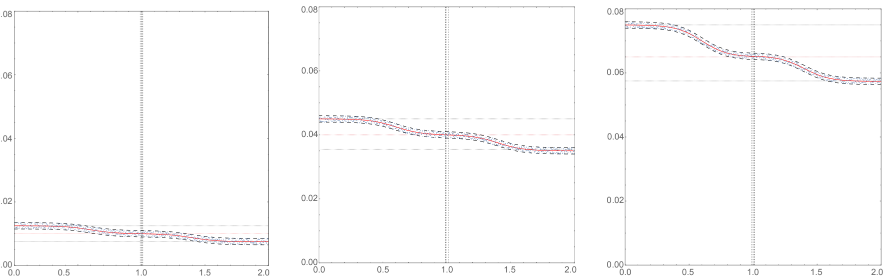
with

$$g(\Gamma_t) = \frac{1}{2} + \frac{1}{2}\tanh\left(\frac{\Gamma_t - 1}{0.1}\right) \quad \text{and} \quad \varphi = 5. \tag{5}$$

The parameters $\sigma_1, \sigma_2, \sigma_3$ and σ_4 are implemented to take the fact into account that it seems to be a property of FED funds data[16] in the past that the CB's interest corridor or, put differently, the interest spread between borrowing from and depositing at the CB increases with the level of the target rate i_t^*. We guess that if monetary aggregates increase along with economic activity, the CB intents to provide more scope for banks to reallocate reserves among themselves through interbank lending before turning to the (more

[15] Lavoie (2003) describes the situation in which the financial system only consists of two (highly specialized) banks whereas one of them only collects deposits while the other only grants loans to the real sector. As a result of the incentive scheme framed by the interest corridor of the central bank's standing facilities, banks have a huge incentive to reallocate the amount of outstanding reserves among each other (through interbank lending) without involving the central bank's balance sheet.

[16] For example, the Federal Reserve Bank of St. Louis provides appropriate data sets of the federal funds rate showing such a feature (http://research.stlouisfed.org/fred2/).



(a) Low interest level **(b)** Mid interest level **(c)** High interest level

Figure 4: Interest corridor of the CB for varying target rate levels

expensive) standing facilities to ensure a smooth functioning of the interbank market. Therefore, we decided to (stepwise) widen the spread for higher levels of i_t^*, i.e. we define a low ($i_t^* < 3\%$), mid ($3\% \leq i_t^* \leq 5\%$), and high ($i_t^* > 5\%$) interest environment with appropriate spreads for the standing facility corridor. Figure 4 shows the corresponding plots for target rates lying within each of the three ranges. Therefore, the calculation of $i_{b,t}^{MM}$ in equation (4) is carried out accordingly by depending on $\sigma_1, \sigma_2, \sigma_3$ and σ_4. The corresponding parameterization can be found in Table 1.

Moreover, Figure 5 provides an overview of the possible spreads in the model whereas the area $B+C$ represents all possible locations of $i_{b,t}^{MM}$. These spreads form the incentive scheme for banks determining what to do with their liquidity, i.e. since $i_{b,t}^{Loan} > i_t^* > i_t^{OSDF}$ holds, meeting the real sector's demand for credit has the highest priority whereas lending excess reserves to peers or placing them at the CB plays a subordinated role.[17]

Finally, for the (unsecured) overnight interbank lending to take place, the borrowing bank sends a request to all peers whereas the ones with excess

[17] This means that the modeled CB is, in general, able to stimulate banks' lending activity by lowering its target rate. In reality, this may not always be the case. The recent past has shown that the European Central Bank's (ECB) endeavor to foster lending to the real sector by providing an interest level near and even below the Zero Lower Bound (ZLB) was most widely unsuccessful due to paralyzed markets and the lack of confidence.

Table 1: Parameter sets determining the level of the CB's interest corridor

i_t^*	i_t^{OSDF}	i_t^{OSLF}	σ_1	σ_2	σ_3	σ_4
$i_t^* < 3\%$ (low)	$\max(i_t^* - 0.25\%,\ 0.25\%)$	$i_t^* + 0.25\%$	$\sigma_3 - 0.0025$	0.00125	0.06125	0.00125
$3\% \leq i_t^* \leq 5\%$ (mid)	$i_t^* - 0.45\%$	$i_t^* + 0.5\%$	$\sigma_3 - 0.005$	0.0025	0.0625	0.0025
$i_t^* > 5\%$ (high)	$i_t^* - 0.75\%$	$i_t^* + 1\%$	$\sigma_3 - 0.00865$	0.004	0.065	0.005

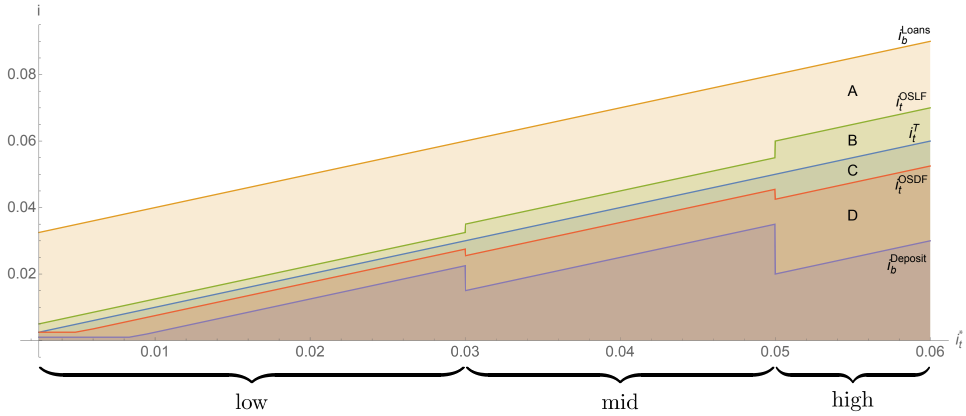


Figure 5: Overview on interest spreads

reserves respond with an offer consisting of the amount of reserves they are willing to lend and the interest charged, i.e. $i^{MM}_{b,t}$. If the borrowing bank agrees on the offered conditions, the lending bank transfers the reserves to the borrower. At the beginning of the next settlement day, the borrower has to repay the borrowed reserves including the interest.

C. *Operating Standing Facilities (OSF)*: Banks use the OSF for two reasons, either the amount of outstanding reserves (which is still only a fraction of interest-bearing deposits) is sufficient and the interbank lending is somehow distorted preventing an efficient reallocation of reserves or the transaction volume exceeds the amount of outstanding reserves or a combination of both. In such situations, the CB provides liquidity insurance for banks by means of standing facilities which can be used against collateral at the end of each settlement day. By charging a premium of $i^{OSLF} - i^*_t$ (discount of $i^*_t - i^{OSDF}$) on i^*_t for the usage of its lending (deposit) facility, the CB builds an interest corridor which ensures that banks seek money first in the open (interbank) money market and reallocate outstanding reserves through overnight repos with peers before turning to the CB's standing facilities [compare Lavoie (2003)].

In summary, it can be said that the CB acts as settlement agent within the real time gross settlement (RTGS) system by providing settlement accounts for banks with access to intraday and overnight liquidity, i.e. the CB provides liquidity insurance [Bank of England (2014a); Dent and Dison (2012)]. In turn, these mechanisms frame the incentive for banks to internally reallocate reserves through the interbank market underpinning its central role within the monetary system since interbank rates are a key target of the CB's monetary policy implementation.

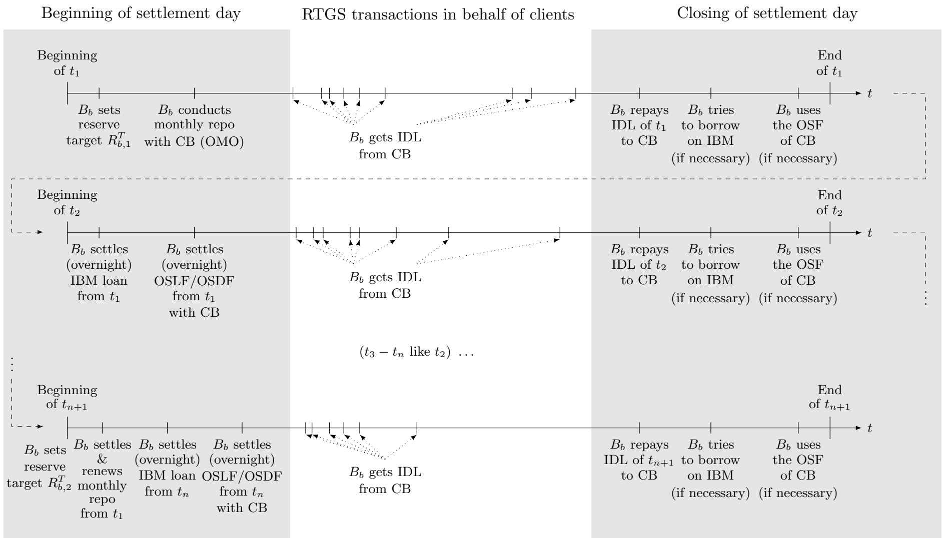


Figure 6: Reserve account settlement within the RTGS monetary system [see Bank of England (2014b)]

Hence, banks have full control over their end-of-period reserve balances but not over the costs associated with the liquidity management mechanisms to achieve their individual reserve target range. Therefore, the underlying monetary framework empowers the CB to fully control the price for liquidity and, thus, economic activity within the model. By way of example, Figure 6 shows how banks settle their reserve accounts with the CB during the maintenance period through the RTGS system and what options it provides.

2.5 Real Sector Activity (Planning Phase)

Firm's Production Target The technology of firms follows the work of Stolzenburg (2015) where the author implements parts of the famous *Solow growth model* into an agent-based framework [Solow (1956)]. Hence, each firm f (with $f = 1,\ldots,F$) determines its production target $q^*_{f,t}$ in period t (the target stays fixed for the next quarter) according to a simple heuristic. This heuristic ensures that the capacity utilization is always slightly above the sales of the past quarter (s_f) in order to enable the firm to accommodate demand fluctuations. The target value for the firm's capacity utilization is set to

$$U^* = \frac{\sum_{s=t-12}^{t-1} s_{f,s}}{q^*_{f,t}} = 0.75, \tag{6}$$

i.e. $U^* < 1$ leads to an expected additional production capacity exceeding past sales $s_{f,t}$ by $\left(\frac{1}{U^*} - 1\right) s_{f,t}$. Hence, the firms production target is set according to

$$q^*_{f,t} = \frac{\sum_{s=t-12}^{t-1} s_{f,s}}{U^*}. \tag{7}$$

Firm's Offered Wage Every household (HH) h (with $h = 1, \ldots, H$) starts with an initial labor skill ψ_h that is a random draw from a truncated normal distribution, i.e. $\psi_h \in \max[0.5, \sim \mathscr{N}(2, \sigma^2)]$, and it determines both the household's individual initial productivity and its wage level. The wage per unit of labor skill $w_{f,t}$ offered by firms on the labor market also follows a simple heuristic with an update frequency of once per quarter. This means that the wage per unit of labor skill from the previous quarter, $w_{f,t-12}$, grows at the same rate as the labor productivity $\left(g_A^Q\right)$ and also takes current expected inflation (π_t^e) as well as the firm's weighted employment gap ($\Xi_{f,t}$) into account. Current expected inflation means a weighted sum of annualized monthly inflation rates of the past two years influenced by the CB's inflation target π^* times the CB's credibility parameter $\chi_\pi = 0.25$, i.e.

$$\pi_t^e = \chi_\pi \pi^* + (1 - \chi_\pi) \sum_{s=1}^{T_\pi} \pi_{t-s}^m \frac{1 + T_\pi - s}{\frac{1}{2} T_\pi (1 + T_\pi)}. \tag{8}$$

Moreover, $w_{f,t}$ also depends on the firm's weighted employment gap ($\Xi_{f,t}$) as an indicator of the firm's ability to hire enough workers to meet its production target given its current offered wage, i.e.

$$\Xi_{f,t} = 1 - \sum_{s=1}^{T_\Xi} \frac{q_{f,t-s}}{q^*_{f,t-s}} \cdot \frac{1 + T_\Xi - s}{\frac{1}{2} T_\Xi (1 + T_\Xi)}. \tag{9}$$

Thus, firm f sets its wage offered for a unit of labor skill according to

$$w_{f,t} = w_{f,t-12} \left[\exp\left(g_A^Q\right) + \pi_t^e + \omega_\Xi \Xi_{f,t}\right] \tag{10}$$

Firm's Credit Demand In order to finance its planned production in advance, firms request loans $\mathscr{L}_{f,t}$ from banks with a maturity of 10 years. The volume of the requested loan mainly depends on the expected weekly labor costs that would occur if the firm would be able to hire a sufficient amount of workers to produce its previously planned production target $q^*_{f,t}$, i.e.

$$q_{f,t}^{-1}\left(q^*_{f,t}\right) w_{f,t}. \tag{11}$$

Here, $q_{f,t}^{-1}(\cdot)$ means the inverse production function giving the units of labor skill needed to produce a given amount of output (here the firm's production target $q^*_{f,t}$).

Assets	Liabilities
Equity Stake ($ES_{h,t}$)	
Bank Deposits ($D_{h,t}$)	
Gov. Bonds ($B_{h,t}$)	Equity ($E_{h,t}$)
Total Assets ($TA_{h,t}$)	

(a) Balance Sheet 3: Example HH h

Assets	Liabilities
Inventory ($Inv_{f,t}$)	Debt Capital ($L_{f,t}$)
Bank Deposits ($D_{f,t}$)	Interest Obl. ($IO_{f,t}$)
	Equity ($E_{f,t}$)
Total Assets ($TA_{f,t}$)	

(b) Balance Sheet 4: Example firm f

Figure 7: Real sector agents' balance sheet structure

So, the term just multiplies the needed units of labor skill with the wage offered per unit of labor skill. Since the weekly labor costs have to be paid during the next quarter, it has to be multiplied with twelve. Moreover, firms add a markup of 10% ($\kappa = 1.1$) on top of the expected labor costs to have an appropriate financial margin for their operational business:

$$\mathscr{L}_{f,t} = \max\left[0,\ 12\kappa \cdot q_{f,t}^{-1}\left(q_{f,t}^{*}\right) w_{f,t} - D_{f,t}\right]. \tag{12}$$

Equation (12) shows that firms prioritize internal financing since they only have a positive demand for bank loans if their current funds ($D_{f,t}$) are insufficient to cover the expected labor costs. If this is the case, firm f sends a request for the loan to its relationship bank. See Figure 7 for an overview of the firm's balance sheet.

Firm Agents Request Bank Loans The endogenous provision of credit money to firms represents the heart of commercial banks' (traditional) business model. The granting of loans is based on a three-stage decision process:

1. After receiving a loan request from a firm, the bank proofs whether it would still comply with the regulatory requirements if it would grant the loan. Thus, the firm can only receive credit money if the bank's balance sheet provides enough regulatory scope to make more loans without violating financial regulation. A violation can have several reasons and can violate either the non-risk based or risk-based capital requirements or both. Thus, the granting of the requested loan can either lead to a violation of the leverage ratio due to the loan volume or to an increase in bank's risk-weighted assets (RWA) which might become too large because the client already exhibits a very high indebtedness. In contrast, a violation of the capital buffers (capital conservation and countercyclical buffer) would not restrict any lending activity, since it would just lead to a (temporary) payout block of dividends.

2. In case of a positive finding, bank b, in a second step, decides on the interest to charge on the requested loan of firm f (i.e. $i_{b,f,t}$) by consulting a simple

internal risk model to evaluate the firm's creditworthiness. Thus, $i_{b,f,t}$ moves in lock-step with the target rate i^*_t and includes a basic mark-up of 2% as well as a firm-specific risk premium. The risk premium reflects the firm's ability to generate sufficient revenues ($Rev_{f,t}$) to meet its future debt obligations ($Oblig_{f,t}$) during the fiscal year. The premium equals 10% if the firm has generated an amount of revenues that exactly equals its potential debt obligations and declines with the amount the revenues exceed the debt obligations as it decreases the risk of a credit default. The risk premium has a maximum of 15%. Hence, the offered interest on the requested loan is determined as

$$i_{b,f,t} = i^*_t + 0.02 + \underbrace{\min\left(0.1 \cdot \frac{\sum_{s=t}^{t+48} Oblig_{f,s}}{\sum_{s=t-48}^{t-1} Rev_{f,s}},\ \ 0.15\right)}_{\text{risk premium}}. \tag{13}$$

Note that, in the model, the actual firm-specific risk premiums are significantly lower than 10% which merely serves as a benchmark since the revenues usually exceed the firm's debt obligations. After this evaluation process, the bank responds to the loan request of the firm by offering the corresponding conditions.[18]

3. The third and final step involves the firm's evaluation on the profitability of the investment given the offered loan conditions. This decision is based on the internal rate of return which is represented by the fact that the probability to take the loan $\mathscr{L}_{f,t}$ under the offered conditions, negatively depends on the offered interest rate $i_{b,f,t}$, i.e.

$$\Pr\left(\mathscr{L}_{f,t} \mid i_{b,f,t}\right) = \max\left[1.8 - 7.5 i_{b,f,t},\ \ 0\right]. \tag{14}$$

Hence, there might be cases in which the firm does not take the loan due to the bank's high risk premium as a result of the firm's poor ability to generate a sufficient amount of revenues. In these cases of a loan rejection, the firm can only employ an amount of workers appropriate to its internal financing capacity. So, in line with the endogenous money theory, the money supply depends on the current indebtedness of the real sector (implicitly via the regulatory channel) and on the CB's current monetary policy decisions.

If the firm accepts the offered loan conditions, the bank grants the requested loan, credits the firm's bank account and generates also a corresponding loan asset and interest receivable on its balance sheet.

[18] There is also the possibility of only *partially* granting the requested loan, but following a survey of the ECB, these cases are only of minor importance. The decision process used here represents over 80% of decisions made by banks within the Euro area [ECB (2010)].

Workforce Adjustment Now, the financial dimension of the planning phase is completed and firms head to the labor market to search for the appropriate amount of workers that they need to realize their planned production target.

Of course, there can also be the case in which a firm has too much employees and current production is higher than the newly planned production target, i.e. $q_{f,t} > q^*_{f,t}$. In such a case the firm fires an adequate amount of workers.

2.6 Government Pays Unemployment Benefit to Unemployed Households

Now the government pays unemployment benefit to all currently unemployed households. The amount paid is adjusted every year to incorporate recent price developments in order to ensure that every household can afford a minimum amount of the good bundle.

2.7 Real Sector Activity (Production Phase)

Labor Market Activity At this stage of the simulation, unemployed households start searching for a job out of a fraction ($\alpha = 0.95$) of all offered vacancies. On the labor market, households offer their labor skill and firms search for an amount of workers that satisfies their specific labor skill demand. If there are any matchings, i.e. if the household faces vacancies in its currently observed subset of all vacancies that demand at least $\psi_{h,t}$, it is hired by a random firm from this individual subset and stays unemployed otherwise.

Production of Goods The production function for the weekly output faced by firm f ($q_{f,t}$) is of the Cobb-Douglas-type and depends on the aggregate labor skill currently employed by firm f ($\Psi_{f,t}$) as input and on the technology parameter A_t representing technological progress. Thus, the labor productivity of households grows at a constant exogenous rate of $g_A = 0.012$ annually (or $g_A^Q = 0.003$ per quarter), i.e. is adjusted every quarter (every 12 weeks) according to

$$A_t = A_{t-12} \exp\left(g_A^Q\right). \tag{15}$$

Hence, firms produce the amount of goods according to their production function of

$$q_{f,t} = \left(A_t \Psi_{f,t}\right)^{1-\alpha} \qquad \text{(with } \alpha = 0.2\text{)} \tag{16}$$

while it depends on the firm's ability to hire enough workers on the labor market whether it is able to meet its production target or not. Note, that one unit of the produced good represents a whole bundle of goods in order to also be able to consume continuous instead of just discrete amounts of the good.

Price Setting To set the retail price for a unit of the produced bundle of goods, firms add a markup on expected unit costs ($\mu > 1$) and account for expected inflation (π_t^e)

$$p_{f,t} = (\mu + \pi_t^e) \cdot \frac{12 \cdot q_{f,t}^{-1}\left(q_{f,t}^*\right) w_{f,t} + \mathscr{L}_{f,t} i_{b,f,t}}{12 \cdot q_{f,t}^*}. \tag{17}$$

The expected unit costs consist of the expected labor costs for the production of the next quarter $\left(q_{f,t}^{-1}\left(q_{f,t}^*\right) w_{f,t}\right)$ and expenses for interest on bank loans ($\mathscr{L}_{f,t} i_{b,f,t}$). Again, $q_{f,t}^{-1}(\cdot)$ represents the inverse production function giving the units of labor skill needed to produce a given amount of output.

Once the retail price is determined, the firm agents offer their produced goods and their inventory on the goods market.

Consumption Households plan their individual weekly consumption level ($c_{h,t}^p$) and update it once a quarter. $c_{h,t}^p$ is composed of an autonomous part

$$c_{h,t}^a = 0.18 \cdot \frac{1}{F} \sum_{f=1}^{F} w_{f,t-12} \tag{18}$$

that co-varies with the average wage level of the firm sector from the previous quarter since it is a main driver of goods prices and the consumption level is expressed in monetary units.[19] Moreover, the planned consumption also depends on the current individual financial situation of household h, i.e. on the average weekly income of the previous quarter including received wages, interest on deposits as well as dividends on an accrual basis ($\overline{I_{h,t}}$). Households adjust their consumption plan in response to changes in the average income $\overline{I_{h,t}}$ according to the adjustment speed parameter $\eta = 0.9$:

$$c_{h,t}^p = \eta c_{h,t-12}^p + (1-\eta)\left(c_{h,t}^a + \eta \frac{\sum_{s=t-12}^{t} \overline{I_{h,s}}}{12}\right) \qquad \text{(with } \eta = 0.9\text{)}. \tag{19}$$

The actual consumption of household h in period t ($c_{h,t}$) only deviates from its planned consumption level $c_{h,t}^p$ in the case in which household h cannot afford to consume $c_{h,t}^p$ due to the lack of money or of supply. Thus, household h might be restricted by its current amount of bank deposits $D_{h,t}$ that depend on the surplus of income over expenditures since the beginning of the simulation. The household's sources of income include a mix of wages ($w_{h,t}$) and unemployment benefits ($UB_{h,s}$)

[19] Note, that this does not mean that households receive wages from every firm, it just ensures that the autonomous part of the planned consumption level adjusts to changes in the wage level of the firm sector.

(depending on how long it was unemployed until t) as well as received interest on its bank deposits ($i^D_{h,s}$). Furthermore, at the end of each fiscal year, firms and banks (partially) distribute their profits in form of dividends to the owning households ($d^F_{h,s}$ and $d^B_{h,s}$, respectively). These sources of income are tax deducted with taxes on income ($\tau^I = 0.3$), on capital gains ($\tau^{CG} = 0.25$) and on consumption ($\tau^{VAT} = 0.2$). From these sources of income, the household's expenditures consists of its previous consumption $c_{h,s}$ (until $t-1$) and the investments in a firm or bank if it is stakeholder of a corporation ($e^F_{h,s}$ and $e^B_{h,s}$, respectively). Hence, the bank deposits of household h in period t are determined as follows:

$$D_{h,t} = \sum_{s=1}^{t}(1-\tau^I)w_{h,s} + \sum_{s=1}^{t} UB_{h,s} + \sum_{s=1}^{t} i^D_{h,s} + \sum_{s=1}^{t}(1-\tau^{CG})d^F_{h,s} + \sum_{s=1}^{t}(1-\tau^{CG})d^B_{h,s} - \left[\sum_{s=1}^{t-1}(1+\tau^{VAT})c_{h,s} + \sum_{s=1}^{t} e^F_{h,s} + \sum_{s=1}^{t} e^B_{h,s}\right] \quad (20)$$

Taking all this into account, the actual consumption of household h in period t follows

$$c_{h,t} = \min\left[D_{h,t},\ \eta c^p_{h,t-12} + (1-\eta)\left(c^a_{h,t} + \eta\frac{\sum_{s=t-12}^{t}\overline{I_{h,s}}}{12}\right)\right]. \quad (21)$$

2.8 Real and Public Sector Debt Obligations

Firms Pay Out Wages Since employees work first before they get their well-deserved wages, we see the related payments to the employed household also comparable to a debt position which is why we put it in this section. Wages are paid out at the end of each month so it doesn't have any influence on the consumer behavior just because of the fact that the payment is processed after the consumption of households in the simulation since they plan and smooth their consumption accordingly. Note, that if a firm is not able to pay all of its employees appropriately due to the lack of sufficient funds, it has to declare bankruptcy due to illiquidity reasons.

Interest on Deposits Furthermore, we judge banks' interest payments on deposits in the same light. The development of the interest on deposits and its dependency on the CB's target rate i^*_t can be reviewed in Figure 5 which shows the prevailing interest environment.

Firms Repay Bank Loans The generated revenues of the firms are now used to settle due parts of their obligations from loan contracts, i.e. they make principal payments and pay interest to the banks. Firms pay interest on their outstanding loan stock every month whereas principal payments are due once a year. The yearly principal equals 10% of the face value of the loan ($\mathscr{L}_{f,t}$) since the maturity of bank loans is 10 years. This means that the monthly interest on a bank loan declines over time.[20] If a firm is not able to meet its debt obligations, it exits the market and all financial claims are cleared in such a way that banks have to depreciate the outstanding loans after receiving the proceeds of the liquidation of the firm's assets. That means that in a default event of a firm, the banks receive a pro rata share of the liquid assets of the firm based on their individual share of the firms debt. Moreover, the owning households lose their share of the firm's equity.

Bond Coupon Payment Also the public sector, i.e. the government, has debt obligations stemming from the issuance of government bonds. At this stage of the simulation, the government pays the yearly coupon on the outstanding government bonds and also repays the face value at maturity. Its expenditures for unemployment benefit to households and the interest on outstanding public debt are financed by raising income taxes on wages ($\tau^I = 30\%$), a VAT on the consumption of goods ($\tau^{VAT} = 20\%$), a corporate tax on profits of firms and banks ($\tau^C = 60\%$), and a tax on capital gains ($\tau^{CG} = 25\%$).

2.9 End of Settlement Period t

Real Sector At the end of the settlement day, all economic activity has been done and the time has come to evaluate on the associated results. If settlement period t is also the last settlement day of the fiscal year, the firm sector ends its settlement period by making annual reports. If all went well and the firm f was able to meets its debt obligations during the fiscal year, it determines its profit before taxation $\Pi^{bt}_{f,t}$ as the difference of the period revenues and cost of goods sold (COGS). Revenues are calculated simply by sales (s_f) times corresponding prices of the period of production (p_f). The cost of goods sold include the amount of interest paid for outstanding loans $i^{\mathscr{L}}_f$ and labor costs of the fiscal year, i.e. the units of labor skill hired (Ψ_f) times the wage paid per unit of labor skill (w_f):

$$\Pi^{bt}_{f,t} = s_f \cdot p_f - \left(i^{\mathscr{L}}_f + \Psi_f w_f \right) \tag{22}$$

[20] Concerning the interest receivable positions in the bank balance sheet, the reader we want to mention that, like in reality, the modelled bank lending activity is based on a debt repayment scheme for every single loan. Firms make principal and interest payments which reduce their individual loan and interest due stock. Thus, both bank balance sheet positions, business loans as well as interest receivables, are reduced by each payment made by the debtor. Hence, there is no overstating of equity during the lifetime of the loan. The position is just used for internal convenience in processing the data related to bank lending activity.

In the case of $\Pi_{f,t} > 0$, firms are burdened by the government with a corporate tax so that the profit after tax results from

$$\Pi^{at}_{f,t} = (1 - \tau^C)\Pi^{bt}_{f,t} \qquad (\text{with } \tau^C = 0.6). \tag{23}$$

From the remaining profit after taxation, $\theta \Pi^{at}_{f,t}$ serves as retained earnings to strengthen the internal financing capacity while the residual of $(1-\theta)\Pi^{at}_{f,t}$ (with $\theta = 0.9$) is distributed as dividends to equity holders.

So far, there was only the possibility for firms to go bankrupt due to illiquidity. During the process of the annual report and the updating of the balance sheet positions, it might also be the case that the firm has to shut down due to insolvency, i.e. due to insufficient or non-positive equity. Assuming that the bankruptcy of a firm happened in t, a new firm enters the market in $t + 24 + \rho$ (where ρ is a positive uniformly distributed integer between zero and 48) given that there exists a sufficiently large group of investors.[21]

Financial Sector Now the financial sector also has to settle its accounts in order to end the settlement day. Section 2.4 already describes the following procedure for banks in great detail. First of all, they have to repay the amount of intraday liquidity (IDL) if they have borrowed funds from the CB during the course of the settlement day in order to process a transaction of a customer which exceeded the bank's current reserve balances in volume. If this step is done, banks look at their actual reserve balance after the repayment of the IDL and evaluate its impact on their average reserve holdings over the whole maintenance period. If their current reserve balance would push their average holdings further away or not strongly enough towards their desired target range, they decide to take advantage of the liquidity management mechanisms.

Banks with a reserve deficit try to borrow an amount of reserves that would bring their average reserve holdings back to their target range using the interbank market. Banks have a huge incentive to reallocate reserves among each other before borrowing directly from the CB because this is much cheaper.

Depending on the banks' ability to borrow from (or lend excess reserves to) peers, they might be forced to adjust their average reserve holdings using the standing facilities of the central bank. Since both liquidity management mechanisms involve just overnight loans, banks have to immediately repay the borrowed funds at the beginning of the next settlement day.

If the period t is also the end of the current maintenance period, the central bank pays interest on the banks that were able to achieve an average reserve holdings

[21] Firms which are shut down, do not vanish from the economy. In order to ensure the stock flow consistency of the model, these firms are just inactive until a new group of HH (investors) has enough capital to reactivate the firm [Dawid et al. (2012)].

within their individual reserve target range. The average reserve holdings are remunerated at the central bank's target rate i_t^*.

After the settlement of all accounts, the banking sector follows with its annual reposts. First, every bank determines its profit before tax as a difference of the received and paid interest payments. The earned interest of banks include the interest on loans to firms and to other banks on the interbank market as well as the coupon payments of the government bonds, the interest on reserves from the central bank and the interest earned by depositing excess reserves using the central bank's standing deposit facility. Banks' interest expenditures include the amount paid on deposits and on the borrowed reserves from peers as well as on the usage of the standing facility of the central bank. After the identification of the fiscal year's profit, banks pay corporate taxes. Before they start to distribute the profit to their stakeholders, they evaluate whether they still comply with the regulatory requirements, i.e. in this case the compliance with the capital conservation buffer (CConB) imposed by the financial supervisory authority (also see 2.10 for more details on regulatory requirements). The aim of the CConB is that banks are able to use the additional (buffered) core capital to absorb unexpected losses (e.g. due to volatile valuation of collateral) in order to avoid harmful deleveraging processes. If a bank does not fulfill the requirement, it is burdened with a payout block according to the ratios shown in Table 2 meaning that it is forced to retain (a fraction of) its (current and future) earnings instead of paying out dividends until the conservation buffer is restored.

Of course, also financial institutions are monitored regarding their solvency at the end of fiscal year. In the case of a threatening default of a systemically important bank (SIB), i.e. of a bank that has significant market share and, thus, plays a crucial role for the functioning of the payment system, the government bails out the institution in distress by waiving of deposits and the issuance of new government bonds. This behavior also leads to the fact, that in the case of a banking crisis that

Table 2: Individual bank minimum capital conservation standards of Basel III

Common Equity Tier 1 Ratio	Min. Capital Conservation Ratios (expressed as a percentage of earnings)	Unconstrained percentage of earnings for distribution
4.500% - 5.125%	100%	0%
5.125% - 5.750%	80%	20%
5.750% - 6.375%	60%	40%
6.375% - 7.000%	40%	60%
$>$ 7.0%[a]	0%	100%

[a] The 7.0% CET1 ratio consists of the 4.5% CET1 minimum requirement and the 2.5% conservation buffer.

affects large parts of the financial system, the last bank is always bailed out by the government. Hence, the government prevents the artificial economy from a total failure of the financial system at any time. Finally, the entry mechanism of new banks resembles the one for firms that is explained at the beginning of this section.

2.10 Monetary Policy and Financial Regulation

Monetary Policy Decisions

Since we have described how the CB uses the target rate i_t^* as key instrument to transmit monetary policy in the model (see Section 2.4), we finally have to explain how decisions about its current level are made. The CB follows a standard *Taylor Rule* under flexible inflation targeting in order to ensure price and output stability. Equation (24) can be considered as a benchmark representing the case of conventional monetary policy which does not target any financial stability measure:

$$i_t^* = i^r + \pi^* + \delta_\pi(\pi_t - \pi^*) + \delta_x(x_t - x_t^n) \tag{24}$$

with $i^r = \pi^* = 0.02$ and x_t^n representing the long-term trend of real GDP measured by application of the Hodrick-Prescott-filter (with $\lambda = 1600/4^4 = 6.25$ for yearly data [Ravn and Uhlig (2002)]).

The scheme's inherent interest incentive for banks combined with being in full control of the target rate and, thus, of the prevailing interest corridor, enables the CB to perfectly steer interest rates, indebtedness of the real sector and, hence, economic activity. Figure 8 shows the balance sheet of the central bank agent.

Assets	Liabilities
Loans to Banks ($L_{CB,t}$)	Reserves ($R_{CB,t}$)
Gov. Bonds ($B_{CB,t}$)	Gov. Acc. ($GA_{CB,t}$)
	Equity ($E_{CB,t}$)
Total Assets ($TA_{CB,t}$)	

Figure 8: Balance Sheet 5: Example *CB*

Regulatory Framework

The financial supervisory authority agent aims to ensure the growth-supportive capacity of the financial sector by imposing micro- and macroprudential capital requirements on banks according to the current Basel III accord of the Basel Committee of Banking Supervision (BCBS) [Krug et al. (2015)].[22] So, except for the

[22] We do not explicitly model Basel III's liquidity requirements (LCR and NSFR), since the literature identifies the capital regulation as the most effective pillar. For further analysis on the relationship between banks' liquidity regulation and monetary policy, see e.g. Scheubel and Körding (2013).

leverage ratio of 3%, all capital requirements are *risk-based*, i.e. require a minimum amount of capital in relation to the riskiness of bank b's loan portfolio measured by its individual risk-weighted assets (RWA). Positive risk weights are assigned to assets resulting from loan contracts whereas government bonds have a zero-risk weight. Hence, we calculate the $\text{RWA}_{b,t}$ of bank b in t by assigning risk weights to its granted loans that depend on the current probabilities of default ($PD_{j,t}$) of its debtor firms ($j = f$) and banks ($j = b$). It follows that the $\text{RWA}_{b,t}$ are an increasing function of the debtors' debt-to-equity ratios $\xi_{j,t}$. The debtors' probabilities of default (PD) are determined by

$$PD_{j,t} = \begin{cases} 1 - \exp\left\{-\rho_j \xi_{j,t}\right\} & \text{with prob. } \vartheta \quad \text{and } j \in \{f,\, b\},\ \rho_j \in \{0.1,\ 0.35\} \\ PD_{j,t-1} & \text{with prob. } 1 - \vartheta \end{cases} . \tag{25}$$

The parameter ϑ determines whether the banks apply *point-in-time* ($\vartheta = 1$) or rather *through-the-cycle* ($\vartheta = 0$) PDs. Here, we present the case for $\vartheta = 1$. Moreover, we want to mention that we do not consider any collateral or provisions for loan losses.

Figure 9 shows the relationships between the PD (solid lines) and the assigned risk weights on granted loans (staircase-shaped lines). It also shows the qualitative differences between debtor firms and debtor banks due to their differing business models meaning that a loan to a debtor bank is typically associated with a much higher debt-to-equity ratio for the same risk weight than to a debtor firm. For instance, if bank b has a loan contract with firm f in its portfolio and $\xi_{f,t} = 8$ holds, it follows approximately that $PD_{f,t} = 0.55$ and the risk weight assigned to that particular loan is 60%.

The imposed requirements consist of a required core capital of 4.5% extended by the capital conservation buffer (CConB) of 2.5%, a counter-cyclical Buffer (CCycB) of 2.5% that is set by the CB according to the rule described in Basel Committee on Banking Supervision (BCBS) (2010) and Drehmann and Tsatsaronis (2014); Agénor et al. (2013); Drehmann et al. (2010), i.e. according to the gap of the current credit-to-GDP ratio and its long term trend determined by applying the *Hodrick-Prescott filter*[23] with a smoothing parameter of $\lambda = 1600$ [Ravn and Uhlig (2002)]:

$$CCycB_{t+1} = [(\Lambda_t - \Lambda_t^n) - N] \cdot \frac{2.5}{M - N} \tag{26}$$

[23] In line with the BCBS, the trend here is "*a simple way of approximating something that can be seen as a sustainable average of ratio of credit-to-GDP based on the historical experience of the given economy. While a simple moving average or a linear time trend could be used to establish the trend, the Hodrick-Prescott filter is used in this regime as it has the advantage that it tends to give higher weights to more recent observations. This is useful as such a feature is likely to be able to deal more effectively with structural breaks*" [Basel Committee on Banking Supervision (BCBS) (2010)].

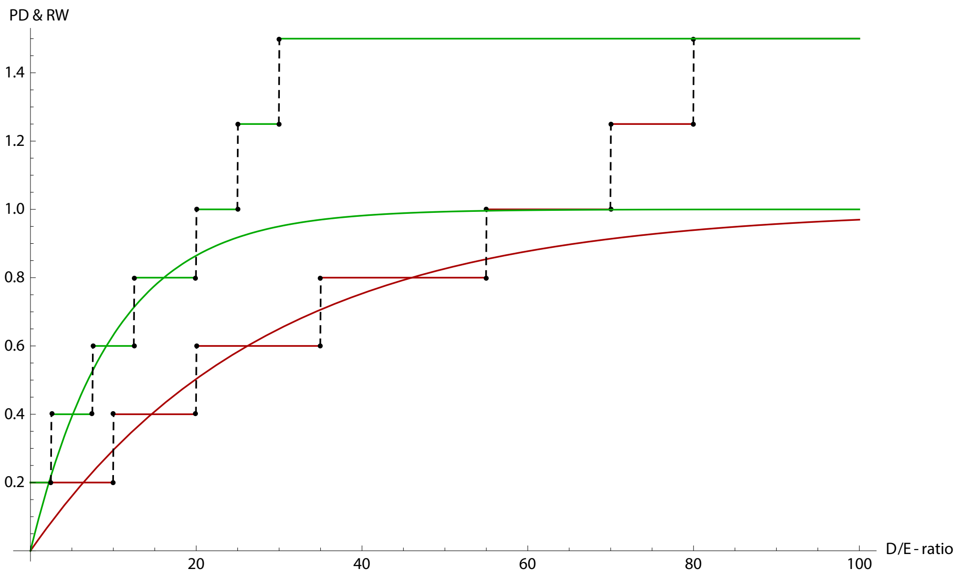


Figure 9: Assigned risk weights according to clients creditworthiness (red for banks, green for firms).

with the credit-to-GDP ratio

$$\Lambda_t = \frac{C_t}{GDP_t}. \tag{27}$$

In line with the regulatory proposal of the Bank of International Settlement (BIS), we set $N = 2$ and $M = 10$.

Finally, we impose surcharges on systemically important banks (SIB) using the banks' market share measured by total assets as indicator for their assignment to the buckets, i.e. if

$$\frac{TA_{b,t}}{\sum_{b=1}^{B} TA_{b,t}} \leq \frac{1+0.3z}{B} \tag{28}$$

holds, b is assigned to bucket $6-z$ for $z \in \{0,\ldots,4\}$. An assignment to bucket 6 means no surcharge and to bucket 2 an extension of the risk-based capital requirement of 2.5% (the highest bucket with a surcharge of 3.5% is empty by definition; compare Table 3).

3 Design of Experiments (DOE)

Mishkin (2011) states that, despite the occurrence of the recent financial crisis and the theoretical deficiencies of general equilibrium frameworks, there is no reason to turn away from traditional new keynesian theory of optimal monetary policy, which caused us to do so in order to measure monetary policy outcomes. According

Table 3: Surcharges on SIBs

Cluster	Score Range	Additional Capital Requirements
5 (empty)	above D[a]	3.5%
4	C - D	2.5%
3	B - C	2.0%
2	A - B	1.5%
1	Cut-off point - A	1.0%
0	*not systemically important*	–

[a] The highest cluster is always empty in order to permanently provide an incentive for banks of the 4th cluster not to grow further.
Note: The size of the clusters depend on the existing set of SIBs, thus, one cannot show explicit score levels for them prior to their evaluation.
Reference: Basel Committee on Banking Supervision (BCBS) (2011)

to Verona et al. (2014), the assessment of the research question formulated above entails three main issues, i.e.

(i) determination of a financial stability measure,

(ii) modeling of the CB's policy response,

(iii) determination of a criterion for policy effectiveness.

Then policy outcomes will be compared in order to show whether crisis mitigation is better achieved with a monetary policy reaction or with financial regulation, i.e. macroprudential policy.

In this regard, the indicator in use for the measurement of financial instability to which the CB should respond to, is, indeed, a crucial issue. Woodford (2012) suggests that, from a theoretical point of view, using financial sector's leverage would be the natural choice. However, Stein (2014) argues that this would be hard to measure in a comprehensive fashion and one should better stick to a broader measure of private sector leverage. He points to the work of Drehmann et al. (2012); Borio and Drehmann (2009); Borio and Lowe (2002) which show that the ratio of credit to the private non-financial sector relative to GDP (the credit-to-GDP ratio) has considerable predictive power for financial crises. Hence, we try to shed some light on these issues by comparing policy outcomes of CB's response to either a measure for the financial sector's leverage which targets a prudent balance sheet structure of the aggregate banking sector [Adrian and Shin (2008a,b)] as well as to the credit-to-GDP ratio.

In order to address (ii), the following paragraph describes the implementation in detail:

- In line with the literature on early warning indicators for financial crises [Babecký et al. (2013); Gadanecz and Jayaram (2009)], we construct a *composite financial stability indicator (CFSI)* and augment the standard instrument rule by the deviation from its target value $CFSI^*$:

$$i_t^* = i^r + \pi^* + \delta_\pi(\pi_t - \pi^*) + \delta_x(x_t - x_t^n) + \delta_s(CFSI_t - CFSI^*) \qquad (29)$$

  with $i^r = \pi^* = 0.02$ and x_t^n representing the long-term trend of real GDP measured by application of the Hodrick-Prescott-filter (with $\lambda = 1600/4^4 = 6.25$ for yearly data [Ravn and Uhlig (2002)]). Moreover, the $CFSI_t$ consists of the average D/E-ratio of banking sector as well as of the inverse of banks' average equity ratio

$$CFSI_t = \log\left(\frac{1}{b}\sum_{i=1}^{b}\xi_{B_i,t}\right) + \log\left(\frac{1}{\frac{1}{b}\sum_{i=1}^{b}\frac{E_{B_i,t}}{RWA_{B_i,t}}}\right). \qquad (30)$$

  As a benchmark, we set $CFSI^* = 6$ which corresponds to an average D/E-ratio in the banking sector of 33 (or an average leverage ratio of approx. 3%) as well as an average equity ratio of 7% core capital, both representing current thresholds of the Basel III accord. This setup leads to an increasing (declining) CFSI if the banking sector gets more fragile (stable) over time.

- In experiments in which the CB responds to jumps in the credit-to-GDP ratio,[24] target rate decisions are guided by

$$i_t^* = i^r + \pi^* + \delta_\pi(\pi_t - \pi^*) + \delta_x(x_t - x_t^n) + \delta_s(\Lambda_t - \Lambda_t^n) \qquad (31)$$

  with Λ_t as defined in eq. (27). The credit-to-GDP gap $\Lambda_t - \Lambda_t^n$ is determined by the difference between the current credit-to-GDP ratio and its long-term trend measured by means of applying the *Hodrick-Prescott filter* with a smoothing parameter $\lambda = 6.25$ [Ravn and Uhlig (2002)].

Concerning (iii), there are two main traditions in the literature. The first one is to search for the policy that maximizes social welfare, i.e. maximizes the utility function of HH, but according to Verona et al. (2014) this approach has some

[24] This has also been analyzed using DSGE models in Cúrdia and Woodford (2010) and Quint and Rabanal (2014).

drawbacks which is why we go for the second one, that is, the policy that best achieves the objective at hand by minimizing loss functions. For the sake of clarity, we take up the approach of Gelain et al. (2013) and differentiate between *(macro)economic* ($L^{MS}_{\delta_s,k,m}$) and *financial stability* ($L^{FS}_{\delta_s,k,m}$). Hence, we define two loss functions in order to easily evaluate outcomes in both dimensions whereby the former is usually defined as the weighted sum of the variances of inflation, output gap and of nominal interest rate changes,[25] i.e.

$$L^{MS}_{\delta_s,k,m} = \alpha_\pi \overline{\mathrm{Var}(\pi_{\delta_s,k,m})} + \alpha_x \overline{\mathrm{Var}(x_{\delta_s,k,m})} + \alpha_i \overline{\mathrm{Var}(i_{\delta_s,k,m})} \tag{32}$$

with $\alpha_\pi = 1.0,\ \alpha_x = 0.5,\ \alpha_i = 0.1$ [Agénor et al. (2013); Agénor and Pereira da Silva (2012)]. The latter, however, addressing financial stability ($L^{FS}_{\delta_s,k,m}$) is defined in terms of the weighted sum of the average burden for the public sector of a bank bailout measured as the fraction of the average bailout costs for the government and the average amount of bailouts ($\overline{\zeta_{\delta_s,k,m}}$) as well as the average amount of bank and firm defaults ($\overline{\rho_{\delta_s,k,m}}$ and $\overline{\gamma_{\delta_s,k,m}}$, respectively), i.e.

$$L^{FS}_{\delta_s,k,m} = \alpha^{FS}\left(\overline{\zeta_{\delta_s,k,m}} + \overline{\rho_{\delta_s,k,m}} + \overline{\gamma_{\delta_s,k,m}}\right) \tag{33}$$

with $k \in \{CFSI,\ \Lambda_t - \Lambda^n_t\}$, $\alpha^{FS} = 0.01$ and
$m \in \{$Basel II (macroprudential policy off), Basel III (macroprudential policy on)$\}$. Hence, the analyzed scenarios add up to 4 since the variables m and k have only two values. While m determines the prevailing regulatory regime, i.e. whether banks have to comply with regulatory requirements in line with the Basel III accord or with its predecessor, namely Basel II, variable k determines the central bank's response to the financial stability measure, which can either be the CFSI or the credit-to-GDP gap. For each of these 4 scenarios, we basically follow the idea of the recent *"model-based analysis of the interaction between monetary and macroprudential policy"* of the Deutsche Bundesbank [Deutsche Bundesbank (2015)] who searches for optimal values of the coefficients in the monetary policy rule using three differing DSGE models including a macroprudential rule. We apply the approach by doing a *grid search* within the three-dimensional parameter space spanned by $\delta_\pi \in [1,3]$, $\delta_x \in [0,3]$ and $\delta_s \in [0,2]$[26] (with a step size of 0.25) whereby the cases of $m =$ Basel II (no macroprudential policy) and $\delta_s = 0.0$ (no leaning against financial imbalances of the CB) represent the benchmark, i.e. a situation that is comparable to the pre-crisis period.

The analysis procedure for raw data produced by the model includes the following steps:

[25] For a deeper discussion of the effects of central bank's interest rate smoothing, see Driffill et al. (2006).

[26] The monthly report of March 2015 of the Deutsche Bundesbank states this parameter space as commonly used for DSGE models and refers to Schmitt-Grohé and Uribe (2007) in this regard.

A. Grid Search We perform a grid search for minimum values of the loss function L and visualize the results using heat maps. Thus, the performance of parameter combinations or data points is evaluated in counterfactual simulations of the underlying agent-based (disequilibrium) macroeconomic model[27] using a set up of 125 HH, 25 firms and 5 banks.[28] Considering every combination of δ_π, δ_x, δ_s, m and k, this adds up to 4212 data points in total. We then conduct Monte Carlo simulations for every data point with random seeds $1,\ldots,100$[29] while every of the 100 runs has a duration of $T = 3000$ periods or ticks. According to our setting, this duration can be translated into approximately 60 years since every tick represents a week and every month has 4 weeks which adds up to 48 weeks for an experimental year. Hence, for the analysis, we take the last 50 years (2400 periods) into account and use the first 600 periods as initialization phase.

B. Identification of Minimum Losses In a second step, we identify areas of best performing parameterizations (minimum losses) and of the corresponding policies. After the generation of the raw output data, we compute the values for the two loss functions $L^{MS}_{\delta_s,k,m}$ and $L^{FS}_{\delta_s,k,m}$. In order to represent the results in two-dimensional space, we additionally compute a combination of $L^{MS}_{\delta_s,k,m}$ and $L^{FS}_{\delta_s,k,m}$:

$$L = \alpha_L L^{MS}_{\delta_s,k,m} + (1-\alpha_L) L^{FS}_{\delta_s,k,m} \tag{34}$$

where α_L represents the weight of the central bank's policy goals. With $\alpha_L = 1$, the CB would just consider its traditional goals of price and output stability whereas $\alpha_L = 0$ would be a solely focusing on financial stability issues. We show relative values for L in panels with δ_π on the abscissa and δ_x on the ordinate for every combination of δ_s, m, k and α_L. Thus, we get $|m| \cdot |k| = 4$ matrices containing $|\delta_s| \cdot |\alpha_L| = 45$ panels. To put the computed results in relation with the benchmark losses (representing 100%), all losses are expressed in percent of their corresponding benchmark loss using a heat map. The displayed range varies from 50% (blue) to 150% (red) of the benchmark. To make this clear, Figure 10 shows a benchmark panel (left panel) and a non-benchmark panel (right panel). Of course, the benchmark panel does not show any blue or red color since it shows a comparison with itself (all data points represent exactly 100%). However, the data point

[27] The ACE Model is programmed in Scala 2.12.4.

[28] We have also conducted experiments with a set up which follows Riccetti et al. (2015) implementing 500 households, 80 firms and 10 banks but the results where qualitatively the same.

[29] We chose only 100 because of the pure amount of data points to simulate and the corresponding time restrictions.

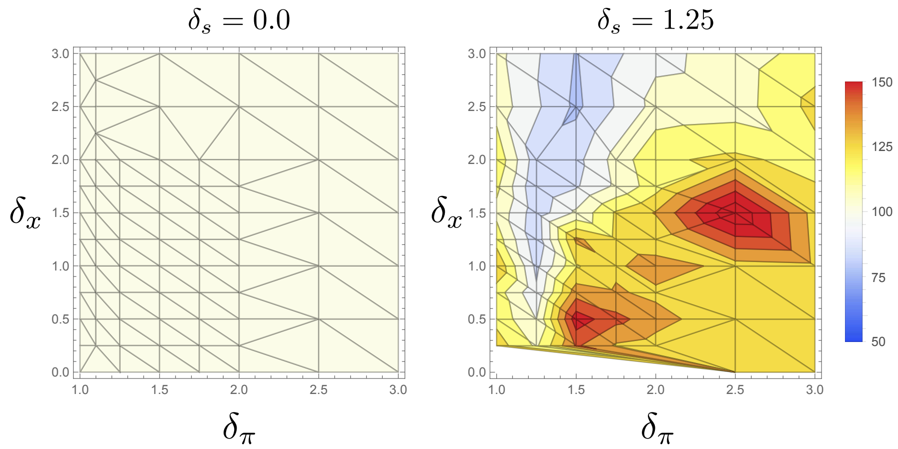


Figure 10: Example for benchmark (left panel) and non-benchmark losses (right panel)

($\delta_\pi = 2.5, \delta_x = 1.5, \delta_s = 1.25$) in the right panel lies in a dark red area which means that, according to our experiments, the underlying policy leads to a much higher loss relative to the corresponding benchmark loss ($\delta_\pi = 2.5, \delta_x = 1.5, \delta_s = 0.0$). Now, we search for all data points lying in dark blue spots to identify minimum losses. The reader can find the results of the grid search for the four analyzed scenarios in Figures 11, 13, 15 and 17.

C. Evaluation of Performance Gains We use violin plots to evaluate how performance gains (minimum losses) can be achieved via policy adjustments and in which way better performing policies differ from the benchmark. These kind of plots extends the usual descriptive statistics of box plots with density plots in order to provide a visualization of the whole distribution of the data. The width of the (rotated and mirrored) density plot represents the frequency of occurrence.

Hence, we show a violin plot for each part of the two loss functions $L^{MS}_{\delta_s,k,m}$ and $L^{FS}_{\delta_s,k,m}$ and, in every plot, we compare the distribution of the parts under the adjusted policy associated with the gain in performance (red density plot) with the corresponding benchmark (blue density plot). In order to avoid a cluttered graph and for the sake of clarity, we decided to forgo the box plot and just show the two density plots in each panel. The reader can find the comparisons of the data points in the Figures 12, 14, 16, 18.

The next section presents the results of the described experiments.

4 Discussion of Results

4.1 Scenario 1: A Monetary Policy Response to Financial Sector Leverage in a Loose Regulatory Environment

Figure 11 shows the losses for the direct response to financial sector leverage in a rather loose regulatory environment (Basel II). If policy makers leave their focus on the traditional monetary policy goals of price and output stability ($\alpha_L = 1$; first row), "leaning against the wind" ($\delta_s \approx 1.0$) has a positive effect on these for common values of δ_π and δ_x. In terms of financial stability ($\alpha = 0.0$; 5th row), results show that such an extension of the central banks' mandate only leads to minor improvements. This stems mainly from the already existing fragility of the system due to the lack of an appropriate regulatory environment. Of course, since there is no conflicting effect or trade-off in the case of $\delta_s > 0$, implementing an extended monetary policy which tries to incorporate also financial stability issues ($\alpha = 0.5$) still leads to a gain relative to the benchmark.

Figure 12 shows how the individual components of the loss functions react to the central bank response in detail. Here, the caution against the consequences of an overreacting monetary policy seem not to be valid. Indeed, the volatility in variances of the target rate increases significantly but at the same time the volatility in the variances of inflation and of the output gap decreases which seem to result in lower firm and considerably lower bank default rates. Also the tail risk for extremely high fiscal costs exhibit a large decline. Note that the axes of each picture in the grid have the same scales as shown in Figure 10 (here they are omitted by intention to increase readability).

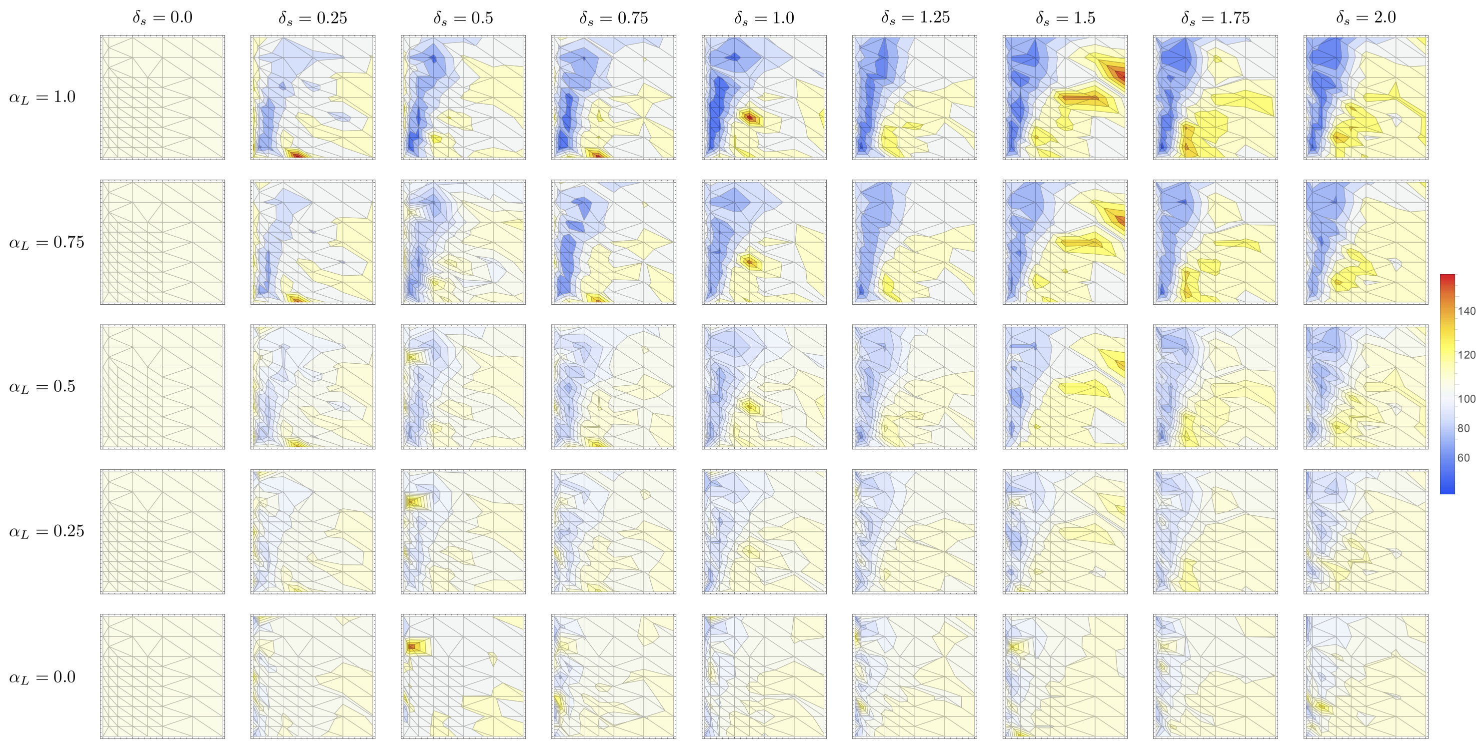
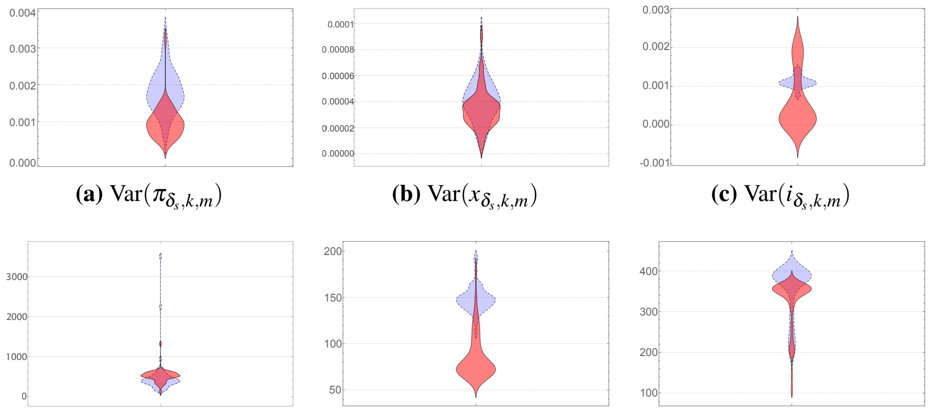


Figure 11: Relative loss of policy 1 (in % of the benchmark case); response to CFSI under Basel II with $\alpha_L \in [1,0]$ in $L = \alpha_L L^{MS}_{\delta_s,k,m} + (1-\alpha_L) L^{FS}_{\delta_s,k,m}$



(a) Var($\pi_{\delta_s,k,m}$) **(b)** Var($x_{\delta_s,k,m}$) **(c)** Var($i_{\delta_s,k,m}$)

(d) $\zeta_{\delta_s,k,m}$ (fiscal costs) **(e)** $\rho_{\delta_s,k,m}$ (bank defaults) **(f)** $\gamma_{\delta_s,k,m}$ (firm defaults)

Figure 12: Minimum loss given a response to CFSI under Basel II; $\delta_\pi = 1.1; \delta_x = 0.25; \delta_s = 1.75;$ $\alpha_L = 1$.
The blue, dashed distribution represents the benchmark scenario while the red, solid one represents the counterfactual scenario.

4.2 Scenario 2: A Monetary Policy Response to Unsustainable Credit Growth in a Loose Regulatory Environment

Figure 13 shows basically the same story for the response to the credit-to-GDP gap, meaning that in a poorly regulated financial system both analyzed transmission channels of monetary policy do not make much of a difference. Again, we can have a look at the composition of minimum losses (Figure 14). This time the volatility in the target rate reduces tremendously likewise with that of inflation. In opposition to the direct tackling of banks' balance sheet structure, a response to jumps in the credit-to-GDP ratio does only seem to have marginal effects on the resilience of the financial system. While the variance in firm and bank defaults increase, the fiscal costs of banking crises just seem to improve in the probability of extreme events. Again, there is no conflict between policy targets meaning that also with a response to unsustainable credit growth as an indicator for financial imbalances, "leaning against the wind" can contribute to the traditional targets of monetary policy.

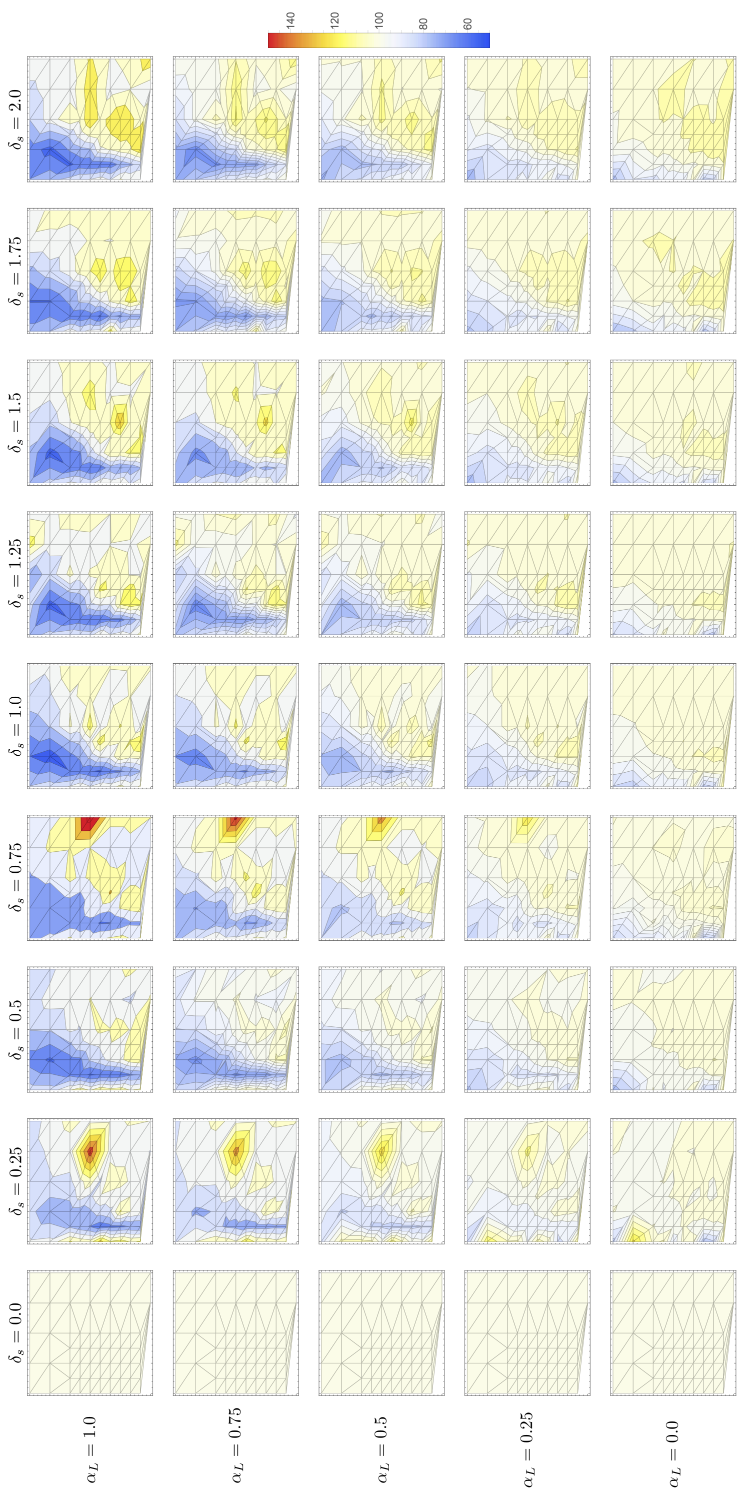
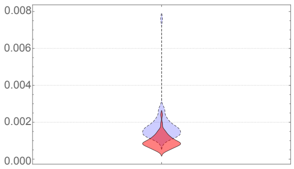
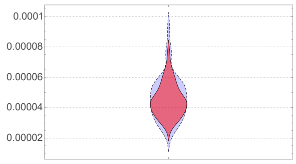


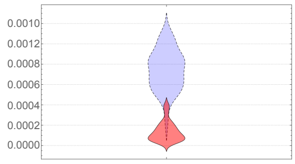
Figure 13: Relative loss of policy 2 (in % of the benchmark case); response to the Credit-to-GDP gap under Basel II with $\alpha_L \in [1,0]$ in $L = \alpha_L L^{MS}_{\delta_s,k,m} + (1-\alpha_L)L^{FS}_{\delta_s,k,m}$



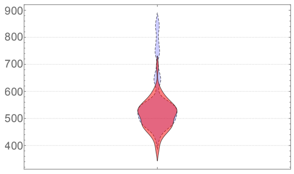
(a) Var($\pi_{\delta_s,k,m}$)



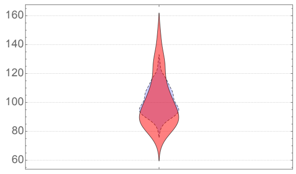
(b) Var($x_{\delta_s,k,m}$)



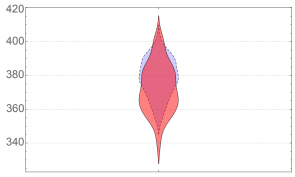
(c) Var($i_{\delta_s,k,m}$)



(d) $\zeta_{\delta_s,k,m}$ (fiscal costs)



(e) $\rho_{\delta_s,k,m}$ (bank defaults)



(f) $\gamma_{\delta_s,k,m}$ (firm defaults)

Figure 14: Minimum loss given a response to the credit-to-GDP gap under Basel II; $\delta_\pi = 1.5; \delta_x = 2.5; \delta_s = 1.0; \alpha_L = 1$.
The blue, dashed distribution represents the benchmark scenario while the red, solid one represents the counterfactual scenario.

To sum up, our results concerning a deregulated system confirm the expected proposition of the Tinbergen principle in the sense that it is not possible to improve financial stability additionally to the traditional goals of monetary policy when addressing both distinct goals (macro and financial stability) using only monetary policy as policy instrument.[30]

4.3 Scenario 3: A Monetary Policy Response to Financial Sector Leverage in a Tight Regulatory Environment

If now the supervisory authorities decide to terminate a period of significant financial deregulation by burdening banks with various prudential requirements, as happened in the aftermath of the recent financial crisis, the picture is somewhat different. With macroprudential policy as a separate and independent policy instrument to tackle financial instability, a supplementary action by the central bank seems to be counterproductive (cf. Figure 15). Given the setting of the current scenario, the loss is minimized if central bankers would use the monetary policy instrument exclusively to target traditional goals, i.e. the common dual mandate, because the tighter financial regulation already serves as first line of defense against banking crises. Thus, any additional intervention via the target rate has a negative impact on the traditional monetary policy goals.

[30] In scenario 1 and 2 the authorities only have the target rate as a policy instrument, since banks are not required to comply with any prudential requirements, i.e. macroprudential policy is not available as a policy tool in these scenarios. This changes in scenarios 3 and 4.

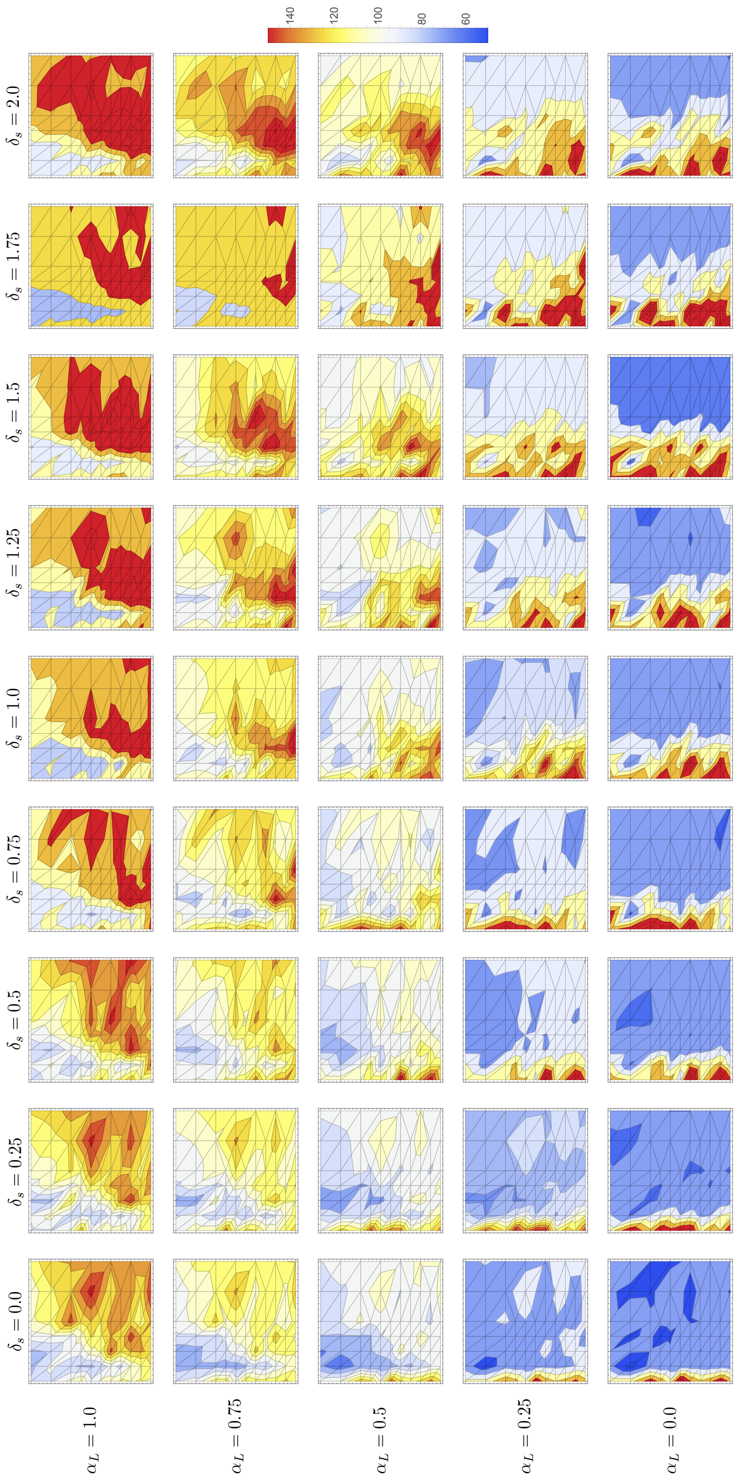
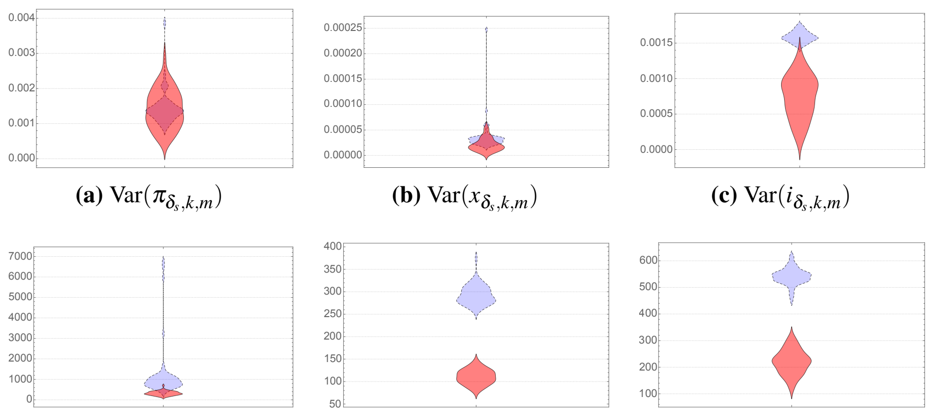


Figure 15: Relative loss of policy 3 (in % of the benchmark case); response to CFSI under Basel III with $\alpha_L \in [1,0]$ in $L = \alpha_L L^{MS}_{\delta_s,k,m} + (1-\alpha_L) L^{FS}_{\delta_s,k,m}$

Moreover, the results show that without an active guidance of economic activity through monetary policy, financial stability cannot be achieved, i.e. losses for $\delta_\pi \approx 1.25$ significantly increase the fragility of the system which underpins the above mentioned common view that inflation can be seen as one of the main sources of financial instability. Hence, our results confirm that, in line with Adrian and Shin (2008a,b), both policy instruments are inherently connected and complementary, thus, influence each other which emphasizes that an appropriate coordination is inevitably and that the prevailing dichotomy of the currently used linear quadratic framework may lead to misleading results.

Having a closer look at the composition of the minimum loss, Figure 16 shows that even without a central bank which "leans against the wind", both the traditional goals of monetary policy as well as the goal of a much safer banking sector seem to be achievable simultaneously leading to positive effects on the real economy. Put differently, the results suggest that a tightening of financial regulation only comes at marginal costs in terms of the central bank's primary goals (macroeconomic stability) but can significantly improve financial stability within the artificial economy. Under the Basel III accord, volatility of inflation rises while volatility of output and interest rates decrease vastly. In contrast, Figure 16d–16f highlight the considerable role of an appropriate degree of financial regulation for the resilience of the financial system. The fiscal costs caused by the need to recapitalize significantly large institutions (government bail outs of banks which are "too big to fail") could be lowered tremendously. This stems mainly from the fact that the tail risk concerning



(a) $\mathrm{Var}(\pi_{\delta_s,k,m})$ **(b)** $\mathrm{Var}(x_{\delta_s,k,m})$ **(c)** $\mathrm{Var}(i_{\delta_s,k,m})$

(d) $\zeta_{\delta_s,k,m}$ (fiscal costs) **(e)** $\rho_{\delta_s,k,m}$ (bank defaults) **(f)** $\gamma_{\delta_s,k,m}$ (firm defaults)

Figure 16: Minimum loss given a response to CFSI under Basel III; $\delta_\pi = 1.25; \delta_x = 2.5; \delta_s = 0.0; \alpha_L = 0$.
The blue, dashed distribution represents the benchmark scenario while the red, solid one represents the counterfactual scenario.

the occurrence of bankruptcy cascades massively boosting fiscal costs could be strikingly decreased by providing an incentive scheme which is sufficiently able to control for banks' risk appetite through the imposition of prudential regulatory requirements. While also the amount of bank defaults decreases significantly, the more interesting part of the results is the effect of a tightened banking regulation on the real sector. The relatively stable range of firm defaults under Basel II (≈ 550 defaults per run) turns into a range with slightly increased variance but with a significantly lower mean. This stems from the fact that banks under Basel III have less lending capacity per unit of capital and also tighter leverage restrictions. At the first glance one might argue that this may lead to non-exhausted growth potential but it rather seems to implicitly restrict lending activity to the already (unsustainable) high-leveraged part of the real sector, dampening the build-up of financial imbalances and, therefore, improving the overall sustainability of economic activity. Hence, the implementation of macroprudential policy has the effect that banks are more cautious in their lending activity since they have to ponder whether to grant a credit to a firm since their lending capacity is much more sensitive to a possible future non-performance of its customers.

4.4 Scenario 4: A Monetary Policy Response to Unsustainable Credit Growth in a Tight Regulatory Environment

For the response to the credit-to-GDP gap, qualitative results are similar to a direct response to unsustainable levels of leverage in the financial sector (scenario 3). $\delta_s > 0$ has almost the same negative impact on the traditional monetary policy goals (see Figure 17). The major difference here is that the resilience of the financial system does improve slightly for moderate levels of δ_s, i.e. the minimum loss given the focus on L_{FS} ($\alpha_L = 0$) is achieved for $\delta_s = 0.5$. But since it is doubtlessly useful to search for the best compromise of both targets, $\delta_s = 0.0$ would be appropriate due to the negative effect on volatility of inflation rates.

Also the composition of the minimum loss differs from a response to the CFSI (see Figure 18), mainly in the higher amount of bank defaults although fiscal costs and firm defaults decline sharply. This phenomenon seems to stems from the conflicting effects of the presence of prudential requirements (positive) and the $\delta_s > 0$ (negative) on the financial system. Thus, there are still cases in which tax payers are burdened with high costs of banking crises but stricter lending standards are clearly beneficial in order to prevent from frequent massive public sector interventions which is in line with the findings of Rubio and Carrasco-Gallego (2014) and Gelain et al. (2013). Also in line with Gelain et al. (2013) is that a direct interest response to excessive credit growth in the central bank's interest rate rule can stabilize output but has the drawback of magnifying the volatility of inflation.

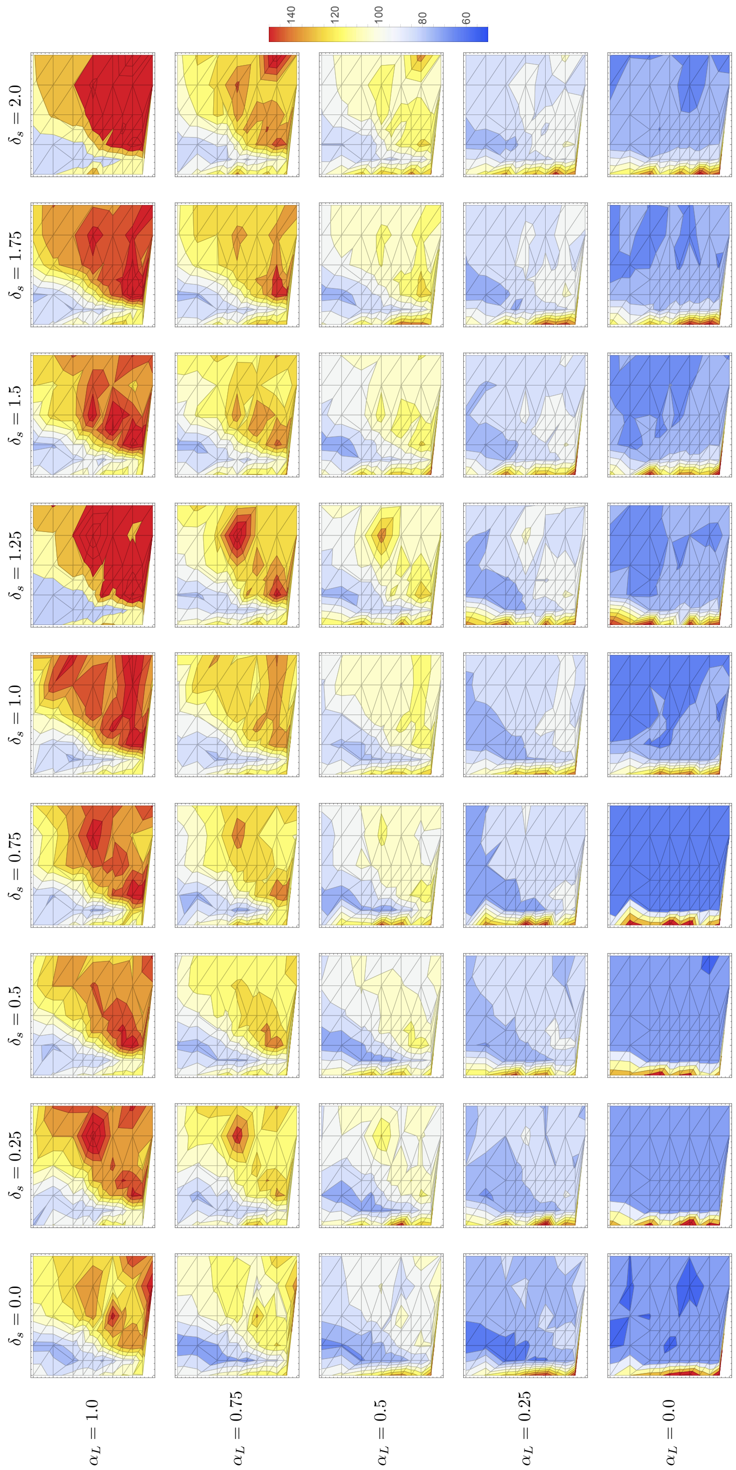
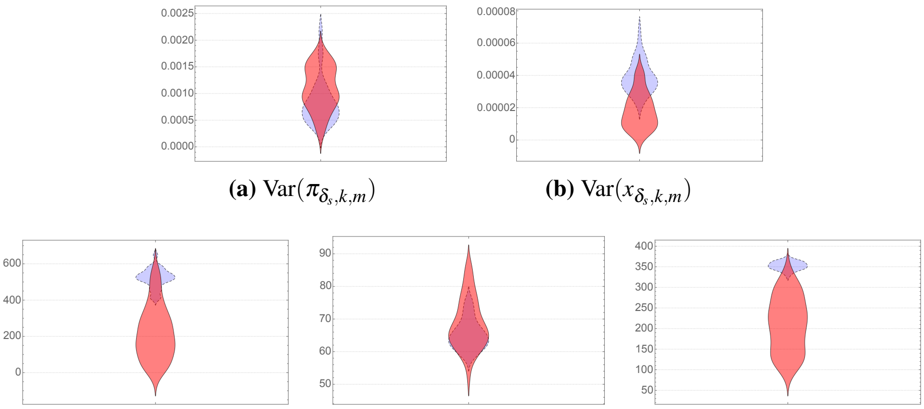


Figure 17: Relative loss of policy 4 (in % of the benchmark case); response to Credit-to-GDP gap under Basel III with $\alpha_L \in [1,0]$ in $L = \alpha_L L^{MS}_{\delta_s,k,m} + (1-\alpha_L) L^{FS}_{\delta_s,k,m}$



(a) $\mathrm{Var}(\pi_{\delta_s,k,m})$ **(b)** $\mathrm{Var}(x_{\delta_s,k,m})$

(c) $\zeta_{\delta_s,k,m}$ (fiscal costs) **(d)** $\rho_{\delta_s,k,m}$ (bank defaults) **(e)** $\gamma_{\delta_s,k,m}$ (firm defaults)

Figure 18: Minimum loss given a response to credit-to-GDP gap under Basel III; $\delta_\pi = 3.0; \delta_x = 0.5; \delta_s = 0.5; \alpha_L = 0$.
The blue, dashed distribution represents the benchmark scenario while the red, solid one represents the counterfactual scenario.

5 Concluding Remarks

The aim of this paper is to shed some light on the current debate on whether central banks should lean against financial imbalances and whether financial stability issues should be an explicit concern of monetary policy decisions or if these should be left to macroprudential regulation and banking supervision. Based on the pre-crisis situation in which financial regulation was way too loose and central banks just focused on their usual dual mandate, there are two policies that have been found adequate to increase the overall resilience of the financial system, i.e. either monetary or macroprudential policy (or a combination of both). So, we also shed some light on the nexus between financial regulation and monetary policy by considering the outcome of policy experiments in terms of macroeconomic and financial stability.

As a framework for the analysis, we present an agent-based macro-model with heterogeneous interacting agents and endogenous money. The central bank agent plays a particular role here since it controls market interest rates via monetary policy decisions which, in turn, affect credit demand and overall economic activity. Therefore, we think that the presented model is well suited to analyze the research question at hand.

Our simulation experiments provide three main findings. First, assigning more than one objective to the monetary policy instrument in order to achieve price, output and financial stability simultaneously, confirms the expected proposition of the Tinbergen principle in the sense that it is not possible to improve financial stability additionally to the traditional goals of monetary policy. The results of our experiments show that after a long phase of deregulation, “leaning against the wind” has a positive impact on price and output stability but affects the rather fragile financial system only marginally. Moreover, in a system in which banks have to comply with rather tight prudential requirements, a central bank’s additional response to the build-up of financial imbalances does not lead to improved outcomes concerning both macroeconomic and financial stability. In contrast, using prudential regulation as an independent and unburdened policy instrument significantly improves the resilience of the system.

Second, “leaning against the wind” should only serve as a first line of defense in the *absence* of prudential financial regulation. If the activity of the banking sector is already guided by an appropriate regulatory framework, the results are in line with Svensson (2012) who argues that *“the policy rate is not the only available tool, and much better instruments are available for achieving and maintaining financial stability. Monetary policy should be the last line of defense of financial stability, not the first line”*. Macroprudential policy dampens the build-up of financial imbalances and contributes to the resilience of the financial system by restricting credit supply to the unsustainable high-leveraged part of the real economy. This strengthens the view that both policies are designed for their specific purpose and that they should be used accordingly.

Third, our results confirm that, in line with Adrian and Shin (2008a,b), both policies are inherently connected and, thus, influence each other which emphasizes that an appropriate coordination is inevitable and that the prevailing dichotomy of the currently used linear quadratic framework may lead to misleading results.

Finally, the present paper is useful to understand that the famous principle of Tinbergen has indeed its justification since extending the objective of monetary policy in order to address additional goals merely transforms the target rate into an overburdened policy instrument that is not able to achieve its traditional policy goals. In this regard, Olsen (2015) is right when arguing that financial regulation probably cannot do it alone and that it needs support but without overburdening monetary policy’s mandate. But this seems to be the crux of the matter. Indeed, there can be done too much when heading towards crises mitigation since additional central bank actions can also result in rather counterproductive activism merely contributing to unintended volatility than strengthening the resilience of the system. In any case, we think that additional research in this area is needed in order to further explore the nexus between monetary policy and financial regulation to avoid such tensions.

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A Model Parameterization

Table 4: Model parameterization

Symbol	Type	Description	Updating	Initialization
B	sub	# of banks	–	5
b	sub	bank b	–	
F	sub	# of firms	–	25
f	sub	firm f	–	
H	sub	# of households	–	125
h	sub	household h	–	
T	sub	# of ticks	–	3000
t	sub	ticks/periods	–	1
α	par	Exponent in firms Cobb-Douglas prod. fct.	–	0.2
α^{FS}	par	Weight of financial stability indicator in loss fct.	–	0.01
α_π	par	Weight of inflation variance in loss fct.	–	1.0
α_i	par	Weight of target rate variance in loss fct.	–	0.1
α_k	par	Weight of CFSI/Credit-to-GDP gap in loss fct.	–	1.0
α_x	par	Weight of output gap variance in loss fct.	–	0.5
χ_π	par	CB credibility parameter	–	0.25
δ_π	par	Instrument param. for price stability in TR	–	1.25
δ_s	par	Instrument param. for financial stability in TR	–	$\in (0, 0.5)$
δ_x	par	Instrument param. for output stability in TR	–	0.25
η_h	par	consumption preference parameter	–	$\sim \mathscr{U}(0, 0.5)$
κ_f	par	External finance factor of firms (10% buffer)	–	1.1
λ	par	Smoothing parameter for HP-filter	–	6.25 / 1600
μ	par	Price mark-up on production costs	–	1.1
ω_Ξ	par	Employment gap param. for wage decision	–	0.005
π^*	par	Inflation target of the CB	–	0.02
ψ_h	par	Labor skill of household h	–	$\max[0.5, \sim \mathscr{N}(2, \sigma^2)]$
τ^C	par	Corporate tax	–	0.6
τ^I	par	Tax on income	–	0.3
τ^{CG}	par	Tax on capital gains	–	0.25
τ^{VAT}	par	Value added tax (tax on consumption)	–	0.2
θ	par	Retained earnings parameter for firm sector	–	0.9
ρ	par	Firm entry parameter	–	$\sim \mathscr{U}(0, 48)$
φ	par	Money Market interest parameter	–	5
σ_1	par	Money Market interest parameter	–	see Table 1
σ_2	par	Money Market interest parameter	–	see Table 1
σ_3	par	Money Market interest parameter	–	see Table 1
σ_4	par	Money Market interest parameter	–	see Table 1
A_t	par	Firm technology parameter	quarterly	1.0
g_A	par	Annual technological progress of firms	–	0.012
g_A^Q	par	Monthly technological progress of firms	–	0.003

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Table 4 – *Continued from previous page*

Symbol	Type	Description	Updating	Initialization
T_π	par	Expected inflation horizon	–	24
T_ψ	par	Employment gap horizon	–	12
U^*	par	Target utilization of firms	–	0.75
CAR	par	Capital adequacy requirement (Basel III)	–	0.045
CConB	par	Capital conservation buffer (Basel III)	–	0.025
M	par	Parameter for determination of CB's CCycB	–	10
N	par	Parameter for determination of CB's CCycB	–	2
Γ_t	var	Excess reserve supply on money market in t	w.n.	
Λ_t	var	Credit-to-GDP ratio in t		
Λ_t^n	var	Long-term trend of the Credit/GDP ratio in t		
$\Lambda_t - \Lambda_t^n$	var	Credit-to-GDP gap in t		
$\Omega_{k,t}$	var	# of days since last bond coupon paym.	weekly	
π_t	var	Annual inflation rate in t	yearly	0.0
π_t^e	var	Expected inflation rate	weekly	0.02
π_t^m	var	Annualized monthly inflation rate	monthly	
$\Pi_{f,t}^{at}$	var	Profit after tax of firm f in t	yearly	
$\Pi_{f,t}^{bt}$	var	Profit before tax of firm f in t	yearly	
$\Psi_{f,t}$	var	Aggregate labor input of firm f in t	weekly	
$\Upsilon_{k,t}$	var	Total days in coupon period of bond k in t	weekly	
$\varepsilon(\xi_{b,t})$	var	Risk premium for interbank lending depending on D/E ratio of bank b	w.n.	
$\Xi_{f,t}$	var	Weighted employment gap of firm f		
$k_{\delta_s,m}$	var	Weight of TR-augmentation in loss fct.		
$\gamma_{\delta_s,k,m}$	var	Weight of bank/firm defaults in loss fct.		
$\rho_{\delta_s,k,m}$	var	Weight of bank bailouts in loss fct.		
$\zeta_{\delta_s,k,m}$	var	Weight of avg. fiscal costs in loss fct.		
$\mathscr{L}_{f,t}$	var	Need for external finance of firm f in t	quarterly	
$B_{CB,t}$	var	Government bonds hold by the CB in t	weekly	0.0
$B_{G,t}$	var	Issued public debt of government in t (bonds)	weekly	0.0
$BL_{b,t}$	var	Business loans of bank b in t	weekly	0.0
C_t	var	Outstanding credit to the real sector in t	weekly	0.0
$CBL_{b,t}$	var	CB liabilities of bank b in t	weekly	0.0
$CFSI^*$	var	CB's target for the CFSI in t	–	6.0
$CFSI_t$	var	Comp. financial stability indicator in t	every 6 weeks	
c_k	var	Coupon of bond k	–	
$c_{h,t}$	var	Actual consumption level of HH h in t	weekly	0.0
$c_{h,t}^a$	var	Autonomous consumption level of HH h	quarterly	0.0
$c_{h,t}^p$	var	Planned weekly consumption level of HH h in t	quarterly	0.0
$D_{f,t}$	var	Bank deposits of firm f in t	weekly	0.0
$D_{G,t}$	var	Bank deposits of the government in t	weekly	0.0
$D_{h,t}$	var	Bank deposits of HH h in t	weekly	0.0

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Table 4 – *Continued from previous page*

Symbol	Type	Description	Updating	Initialization
$D_{G,t}^{CB}$	var	CB deposits of the government in t	weekly	0.0
$d_{h,s}^{B}$	var	Dividends received by HH h from bank b	yearly	
$d_{h,s}^{F}$	var	Dividends received by HH h from firm f	yearly	
$E_{h,t}$	var	Net wealth of HH h in t	weekly	0.0
$E_{f,t}$	var	Net wealth of firm f in t	weekly	0.0
$E_{b,t}$	var	Net wealth of bank b in t	weekly	0.0
$E_{G,t}$	var	Net wealth of the government in t	weekly	0.0
$E_{CB,t}$	var	Net wealth of CB in t	weekly	0.0
$ES_{h,t}$	var	HH h's share of firms/banks	w.n.	0.0
$e_{h,s}^{B}$	var	Investment of HH h for founding bank b	w.n.	
$e_{h,s}^{F}$	var	Investment of HH h for founding firm f	w.n.	
$FV_{k,t}$	var	Face value of bond k in t	weekly	
$GA_{CB,t}$	var	Government account at CB in t	weekly	0.0
$GB_{b,t}$	var	Government bonds of bank b in t	weekly	0.0
$GD_{b,t}$	var	Government deposits of bank b in t	weekly	0.0
i^{r}	var	Real interest rate (long-term)	w.n.	0.02
i_t^{*}	var	CB target rate in t	every 6 weeks	0.01
i_t^{OSDF}	var	Op. standing deposit facility of CB in t	every 6 weeks	0.0075
i_t^{OSLF}	var	Op. standing lending facility of CB in t	every 6 weeks	0.0125
$i_f^{\mathscr{L}}$	var	Interest payments for outst. loans of firm f	w.n.	
$i_{b,f,t}$	var	Loan interest charged by bank b on firm f in t	w.n.	$i_t^{*}+0.03$
$i_{b,t}^{Deposit}$	var	Interest on deposits paid by bank b in t	every 6 weeks	0.0025
$i_{b,t}^{MM}$	var	Money market int. rate faced by bank b in t	w.n.	
$i_{h,s}^{D}$	var	Interest received on $D_{h,t}$ by HH h in s	yearly	
$I_{h,t-12}$	var	Avg. weekly income of HH h of prev. quarter	quarterly	
$Inv_{b,t}$	var	Value of Inventory of firm f in t	weekly	0.0
$IO_{f,t}$	var	Interest Obligations of firm f in t	weekly	0.0
$IR_{b,t}$	var	Interest receivables of bank b in t	weekly	0.0
$L_{\delta_s,k,m}^{FS}$	var	Loss fct. to determine financial stability	–	
$L_{\delta_s,k,m}^{MS}$	var	Loss fct. to determine macroeconomic stability	–	
$L_{CB,t}$	var	CB loans to the banking sector in t	weekly	0.0
$L_{f,t}$	var	Debt capital of firm f in t	weekly	0.0
$n_{k,t}$	var	# of remaining coupon paym. of bond k at t	weekly	
$\Pr\left(\mathscr{L}_{f,t} \mid i_{b,f,t}\right)$		Probability that firm f takes $\mathscr{L}_{f,t}$ given $i_{b,f,t}$	quarterly	
$p_{f,t}$	var	Offered price of firm f in t	quarterly	200.0
$p_{k,t}^{clean}$	var	Clean price of government bonds	weekly	
$q_{f,t}$	var	Actual production of firm f in t	weekly	
$q_{f,t}^{*}$	var	Production target of firm f in t	quarterly	$2H$
$R_{b,t}$	var	Central bank reserves of bank b in t	weekly	0.0
$R_{b,t}^{*}$	var	Reserve target of bank b in t	weekly	0.0

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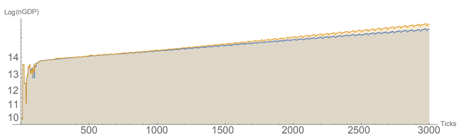
Table 4 – *Continued from previous page*

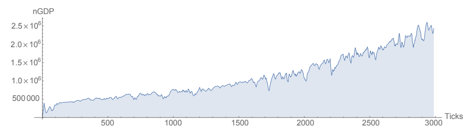
Symbol	Type	Description	Updating	Initialization
$R_{CB,t}$	var	Outst. CB reserves hold by banking sector in t	weekly	0.0
$RD_{b,t}$	var	Retail deposits of bank b in t	weekly	0.0
$RWA_{b,t}$	var	Risk-weighted assets of bank b in t		
$s_{f,t}$	var	Sales of firm f in t	weekly	
$TA_{b,t}$	var	Total assets of bank b in t	weekly	0.0
$TA_{CB,t}$	var	Total assets of CB in t	weekly	0.0
$TA_{f,t}$	var	Total assets of firm f in t	weekly	0.0
$TA_{G,t}$	var	Total assets of the government in t		0.0
$TA_{h,t}$	var	Total assets of HH h in t	weekly	0.0
$UB_{h,s}$	var	Unemployment benefit received by HH h in t	yearly	
$w_{f,t}$	var	Wage per unit of labor skill offered by f in t	quarterly	1000.0
$w_{h,s}$	var	Wage received per unit of labor skill by h in s	quarterly	1000.0
$WL_{b,t}$	var	Wholesale loans of bank b in t	weekly	0.0
$WO_{b,t}$	var	Wholesale deposits of bank b in t	weekly	0.0
x_t	var	Output gap in t	yearly	0.0
x_t^n	var	Potential output in t	yearly	0.0
z	var	Surcharge-bucket assignment parameter		
CCycB_t	var	Countercyclical buffer set by the CB in t	6 weeks	0.0

B Validation of the Model

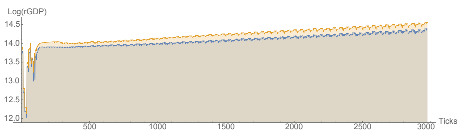
In order to validate the output data and the results of the presented agent-based macro-model, we use this section to jointly replicate a wide range of common empirical regularities like it has been done for other ACE models that are already accepted in the field of policy advice. In this context, the Keynes+Schumpeter model developed in Dosi et al. (2006, 2008, 2010, 2013, 2016, 2015) or the model described in Riccetti et al. (2015) should be mentioned since both show that (decentralized) interactions among heterogeneous agents give rise to emergent macroeconomic properties.[31] In both cases, the authors are able to validate their results by showing in detail how the model's simulated macroeconomic dynamics lead to characteristic patterns and distributions within their experimental data that coincide with real macro data. According to Fagiolo et al. (2007); Fagiolo and Roventini (2012), this is the appropriate approach to show a robust empirical validation of the model framework and, hence, of the "computational lab" leading to plausible and comparable results when testing and analyzing various policy experiments.[32]



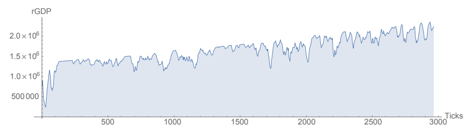
(a) Log Nominal GDP (avg. of 1000 runs; blue for Basel II, orange for Basel III)



(b) Nominal GDP (single run)



(c) Log Real GDP (avg. of 1000 runs; blue for Basel II, orange for Basel III)



(d) Real GDP (single run)

Figure 19: Endogenous nominal/real GDP growth with persistent fluctuations [SF1]

[31] Riccetti et al. (2015) state that *"[i]n particular, simulations show that endogenous business cycles emerge as a consequence of the interaction between real and financial factors: when firms profits are improving, they try to expand the production and, if banks extend the required credit, this results in more employment [;] the decrease of the unemployment rate leads to the rise of wages that, on the one hand, increases the aggregate demand, while on the other hand reduces firms profits, and this may cause the inversion of the business cycle, and then the recession is amplified by the deleveraging process"*.

[32] Dosi et al. (2016) emphasize that this way of model validation, i.e. matching a large number of stylized facts simultaneously, is the way to do it, although it is eminently costly and time-consuming. We can confirm this view.

To the best of our knowledge, the list of stylized facts presented in Table 5 is the list to be met by ACE models for policy evaluation in the macro-finance area. It can originally be found in Dosi et al. (2016) and we chose it as a guide for the validation process of our model because it is the most complete one. Moreover, the table is extended by some additional facts found in Riccetti et al. (2015). Furthermore, we set the number of Monte Carlo simulations to be 1000, i.e. the experiments are repeated with random seeds $1,\ldots,1000$, in order to *"wash away [the] across-simulation variability"* resulting from *"non-linearities present in agents' decision rules and [...] interaction patterns"*. This approach enables us to *"analyze the properties of the stochastic processes governing the co-evolution of micro- and macro-variables"*.

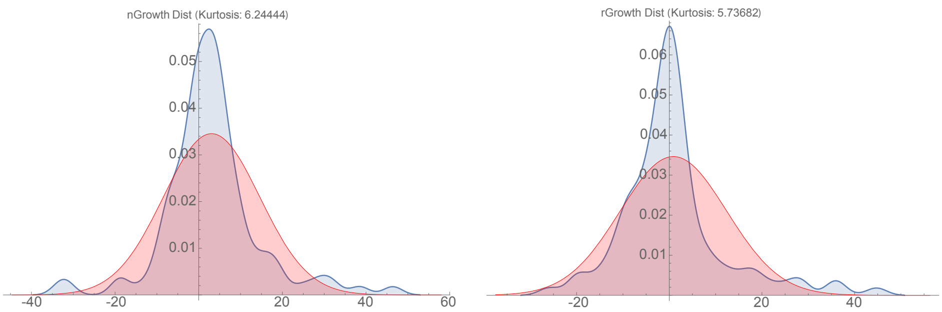
Going through Table 5 step-by-step, the first macroeconomic stylized facts (SF1) would be the ability of the model to produce endogenous and self-sustained GDP growth characterized by persistent fluctuations both in nominal and real terms. Figure 19a shows the average log of nominal GDP for simulations with random seeds $1,\ldots,1000$ which is steadily growing whereas Figure 19b shows exemplary the dynamics of nominal GDP of a single run. The right panel exhibits moderate fluctuations at the beginning of the simulation which are increasing with economic activity and overall size of the economy leading to business cycles including booms

Table 5: Stylized facts replicated by the Keynes+Schumpeter-ACE model [Dosi et al. (2016)]

Code	Stylized fact	Empirical studies (among others)
SF1	Endogenous self-sustained growth with persistent fluctuations	Burns and Mitchell (1946); Kuznets and Murphy (1966); Zarnowitz (1985); Stock and Watson (1999)
SF2	Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi and Dosi (2009)
SF3	Recession duration exponentially distributed	Ausloos et al. (2004); Wright (2005)
SF4	Relative volatility of GDP/consum./invest.	Stock and Watson (1999); Napoletano et al. (2006)
SF5[a]	Pro-cyclical aggregate firm investment	Wälde and Woitek (2004)
SF6	Pro-cyclical bank profits/debt of firm sector	Lown and Morgan (2006)
SF7	Counter-cyclical credit defaults	Lown and Morgan (2006)
SF8	Lagged correlation between firm indebtedness & credit defaults	Foos et al. (2010); Mendoza and Terrones (2014)
SF9	Banking crises duration is right skewed	Reinhart and Rogoff (2009)
SF10	Fat-tailed distribution of fiscal costs of banking crises-to-GDP ratio	Laeven and Valencia (2013)
SF11[b]	the presence of the Phillips curve	Phillips (1958)

[a] In the original table of Dosi et al. (2016), aggregate R&D investments are used. We use, instead, the firm sector's requested amount of loans from banks as a proxy for their investment in the production of goods.

[b] Described as general characteristic of an economy, i.e. without explicit notion of empirical studies and found in Riccetti et al. (2015).



(a) Distribution of nominal GDP growth-rate **(b)** Distribution of real GDP growth-rate

Figure 20: GDP growth-rate distribution (blue) compared to the Gaussian fit (red) [SF2]

and deep downturns. The same holds for real GDP (see Figure 19c/19d). Moreover, the comparison of both time series reveals the fact that the business cycles do not vanish when building the average of various simulation runs but are much more regular.

The second replicated stylized fact directly connects to the first one and follows the empirical studies of Fagiolo et al. (2008); Castaldi and Dosi (2009) where the authors have shown that real data sets of GDP-growth rates have the property of fat-tailed distributions compared to their Gaussian benchmarks. This also holds for our model in both nominal (Figure 20a) and real terms (Figure 20b).

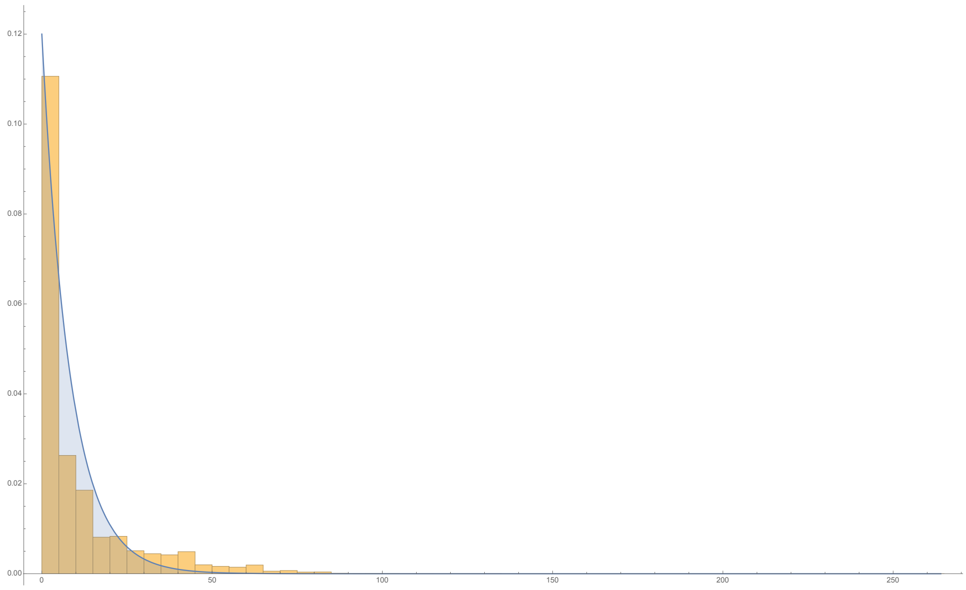


Figure 21: Exponentially distributed duration of recessions [SF3]
Bins represent the data from the model, blue is the exponential fit of the data.

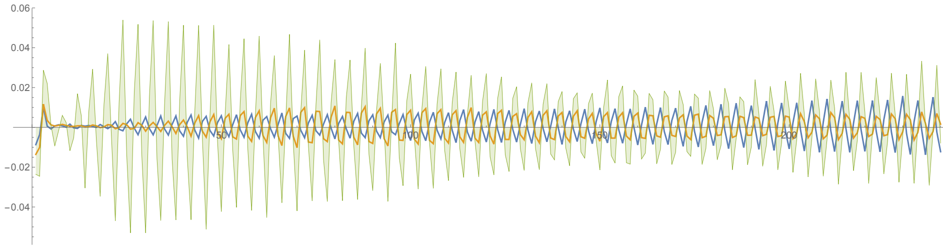


Figure 22: Bandpass filtered time series of GDP/consumption/investments to show their relative volatility [SF4]
Volatility of GDP (blue); of consumption (orange); of investments (green)

Concerning the recessions occurring during the simulations, we can confirm that the majority lasts for rather short periods of time and that their frequency declines substantially with rising duration. Empirical data shows that they are approximately exponentially distributed which is also the case in our experimental data (see Figure 21).

To verify whether our model can replicate SF4, we again follow Dosi et al. (2016) and bandpass filter the time series for GDP, consumption and firm investment in order to de-trend the data and to analyze their behavior at business cycle frequencies. As Figure 22 shows, the data produced by our model is in line with the empirical findings since the fluctuations of consumption are slightly smaller compared to GDP while firm investments is much more volatile than output.

While the stylized facts 1-4 have general macroeconomic character, the following focus on drivers of prevailing economic activity and, thus, the business cycle. This means that the pro- and counter-cyclicality of key variables is essential to ensure the proper functioning of the modeled monetary economy. Overall, they shed some light on the development of the lending activity and on the resulting financial stability dynamics over time. The first fact here is then the pro-cyclicality of firm's aggregate investment which tend to co-move with the business cycle (Figure 23).

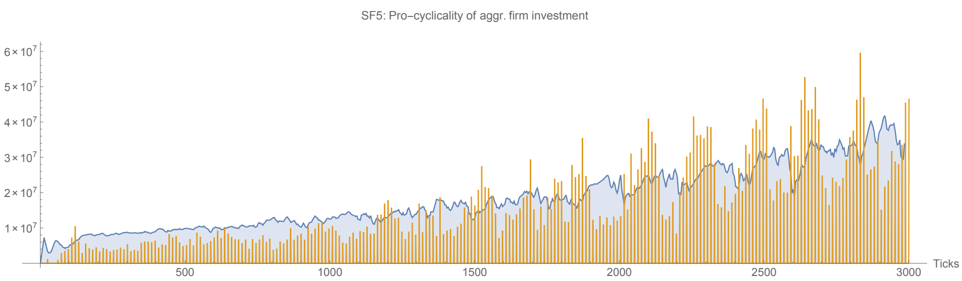
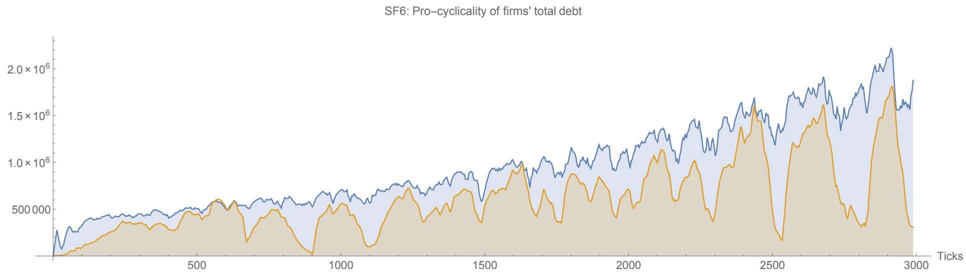
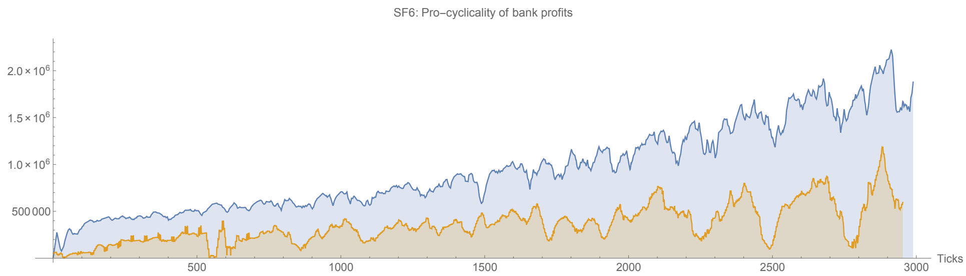


Figure 23: Pro-cyclicality of aggregate firm investments [SF5]
GD (blue); Aggregate firm investment (orange)



(a) Pro-cyclicality of firms' total debt



(b) Pro-cyclicality of bank profits

Figure 24: Pro-cyclical lending activity [SF6]
Ordinate scale relates to GDP (blue); whereas credit related variables (orange) are scaled appropriately to emphasize their pro-cyclicality.

Moreover, Lown and Morgan (2006) have shown empirically, there exists a strong link between the total debt outstanding in the firm sector (24a) and the profits of the banking sector (24b) both being highly pro-cyclical.

Hence, the lending activity co-moves with the business cycle whereas the experience from past financial crises suggests that the build-up of debt imbalances leads to downturns triggered by peaks in default rates which, in turn, result in rather counter-cyclical behavior of credit defaults (25). Figure 25 shows that these facts are also features of our model and can be replicated simultaneously.

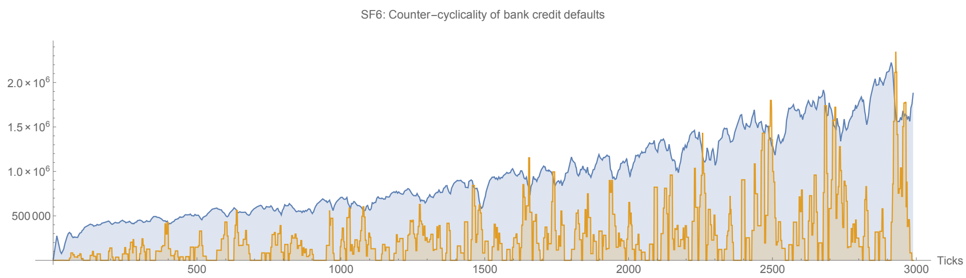


Figure 25: Counter-cyclical credit defaults [SF7]
GDP (blue); credit defaults are measured by loan losses of banks (orange).

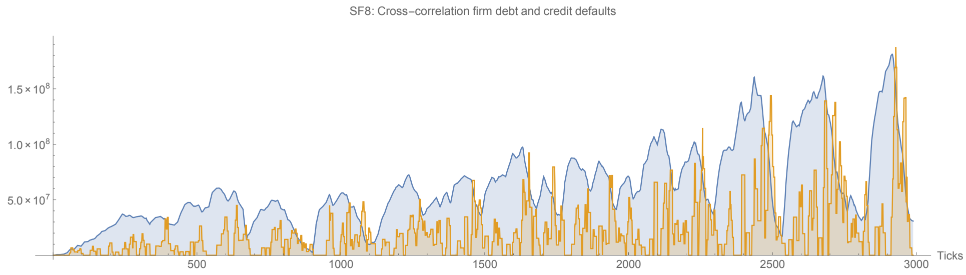


Figure 26: Lagged correlation of firm indebtedness and credit defaults [SF8]
Indebtedness of firm sector (blue); bad debt is measured by loan losses of banks (orange).

Moreover, the slightly lagged correlation between indebtedness of the firm sector and credit default rates can be replicated just as well. Figure 26 validates in a very clear manner that in our experimental data the build-up of real sector debt imbalances is accompanied by banks facing excessive risk of bad debt and, thus, are frequently paired with periods of financial distress translating into economic downturns.

In order to cope with empirical regularities of financial crises data, we then define crises as periods from the first bank default until all banks B are back in their business. Thus, the empirical work of Reinhart and Rogoff (2009) suggests that the distribution of the duration of these periods is positively skewed (right skewed). This also holds for our model (see Figure 27).

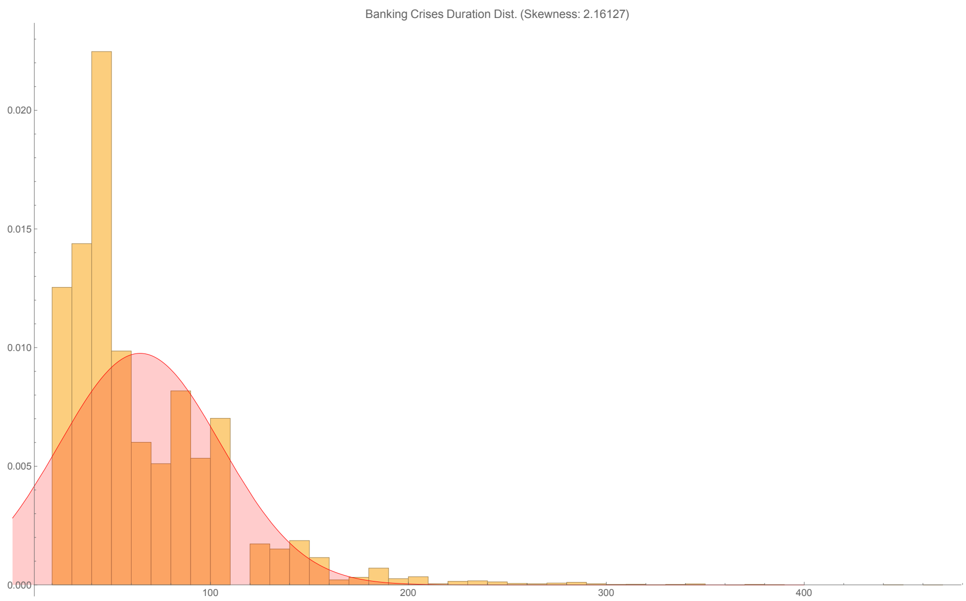


Figure 27: Banking crises duration is right-skewed compared to Gaussian data fit [SF9]

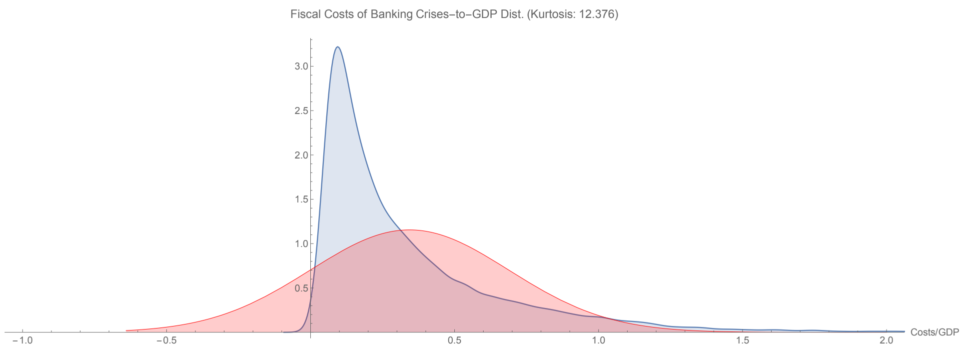


Figure 28: Fat-tailed distribution of fiscal costs of banking crises-to-GDP ratio [SF10]

Moreover, the ratio of fiscal costs-to-GDP is computed for such periods of financial distress. These fiscal or restructuring costs caused by financial crises mainly consists of recapitalization costs to stabilize the banking sector and, in reality, the distribution of the ratio is characterized by excess kurtosis (here above 12), i.e. fat tails, which is also the case in our experiments (see Figure 28).[33] Last but not least, our experimental data exhibits a Phillips curve (Figure 29).

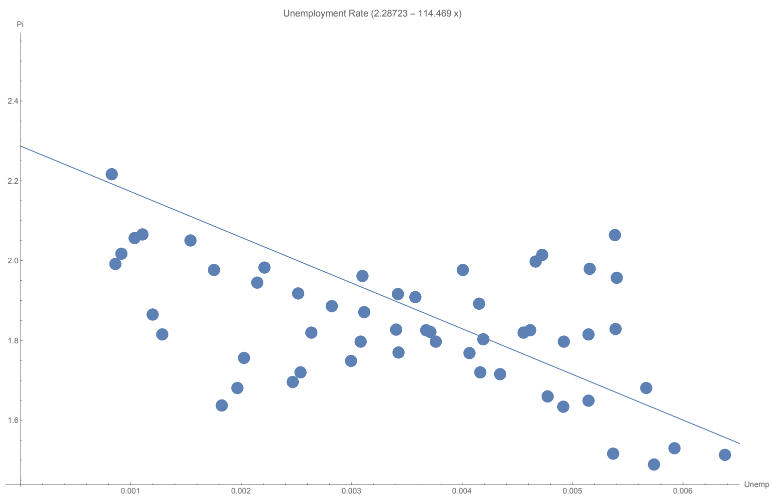


Figure 29: Phillips curve [SF11]

[33] Laeven and Valencia (2013) define a significant support by the government if fiscal costs exceed 3% of GDP. This seems to be a reasonable choice for real data but the typical real economy of interest is considerably larger and consist of more agents compared to our small-scale ACE model. In fact, this affects the fiscal costs-to-GDP ratio since the size of our banking sector relative to GDP is much larger than in reality since our model has less agents to contribute to GDP. Hence, this can lead to years in which the fiscal costs are twice or three times as high as GDP. These relatively high ratios might be comparable to the situation in small countries with large financial systems like Iceland or Ireland where the fiscal costs have reached very high levels amounting even to multiples of GDP.

In summary, the replicated stylized facts shown above indicate the relevance of leverage cycles and credit constraints on economic performance as well as the importance of the government in its function as a compensating and balancing institutional agent providing stability to the economy. Furthermore, this section shows that the presented macro model is generally able to serve as framework for the analysis of research questions concerning banks lending activity, leverage, financial crises as well as monetary and macroprudential policy.