BUBBLES, CRASHES, AND THE FINANCIAL CYCLE: THE IMPACT OF BANKING REGULATION ON DEEP RECESSIONS

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This paper explores how different credit market and banking regulations affect business fluctuations. Capital adequacy- and reserve requirements are analyzed for their effect on the risk of severe downturns. We develop an agent-based macroeconomic model in which financial contagion is transmitted through balance sheets in an endogenous firm-bank network, which incorporates firm bankruptcy and heterogeneity among banks to capture the fact that contagion effects are bank specific. Using concepts from the empirical literature to identify amplitude and duration of recessions and expansions, we show that more stringent liquidity regulations are best to dampen output fluctuations and prevent severe downturns. Under such regulations, both leverage along expansions and amplitude of recessions become smaller. More stringent capital requirements induce larger output fluctuations and lead to deeper, more fragile recessions. This indicates that the capital adequacy requirement is procyclical and therefore not advisable as a measure to prevent financial contagion.

Keywords: Financial Crises, Credit Market and Banking Regulations, Financial Fragility, Agent-Based Macroeconomics

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1. INTRODUCTION

The agenda of this paper is to improve our understanding of the mechanisms responsible for business fluctuations and to explore how the amplitude of such fluctuations is affected by different types of banking and credit market regulations. It is well documented that business fluctuations are associated to substantial welfare costs [see, e.g., Gali et al. (2007)] and these costs are particularly severe for deep recessions. Such severe downturns are typically associated with massive job losses and firm bankruptcies, which induce a substantial reduction in physical and human capital, thereby negatively affecting not only current output but also growth perspectives [see, e.g., Verho (2008) or Berkmen et al. (2012) for treatments of the potentially negative long-term effects of recessions]. As many historical examples show, severe recessions also induce an increased danger of political instability and the erosion of trust in valuable economic institutions, as witnessed, for example, by the bank runs and subsequent banking panic during the Great Depression. But also more recently, the antiausterity demonstrations across Europe are showing a growing political divide.

Hence, avoiding deep recessions is a particularly urgent goal for economic policy makers, apart from the overall objective of smoothing the business cycle. Whereas a large body of literature addresses the issue of business cycle smoothing, only a small part of this work explicitly addresses the impact of different policy measures on the lower part of the distribution of downturns, i.e., on the severity of the strongest downturns that might occur under different policy scenarios.

This paper focuses exactly on this aspect of business cycle fluctuations and explores to what extent more stringent regulations are suitable tools to avoid severe downturns in an economy. The analysis is carried out in the context of an agent-based macroeconomic model with a strong focus on the firm's financial management and the banking sector. The main part of the model is a credit market embedded in a full-fledged macroeconomic setting with a fully functioning production sector for consumption goods, a labor market, and a market for investment goods (see Figure 1 for an illustration of the model). In the analysis, we include feedback effects from the real sector to the banking sector that might attenuate or exacerbate the procyclicality of the credit and banking regulation. The real sector endogenously generates expansions and recessions, which allows to test whether in scenarios with more restrictive capital or reserve requirements we obtain statistically significant differences in the amplitude and duration of recessions.

In the aftermath of the recent 2007–09 financial and economic crisis, a large body of literature has emerged that aims to capture the feedback effects between financial and real cycles. We contribute to this literature by developing and exploiting a model that endogenously generates cycles in the spirit of Minsky's Financial Instability Hypothesis [see Minsky (1978, 1986)] and captures the main properties of leverage cycles, as described, e.g., in Geanakoplos (2009).

Minsky's characterization of "financial units" according to their cash-flow position classifies corporations as hedge finance, speculative finance, and Ponzi
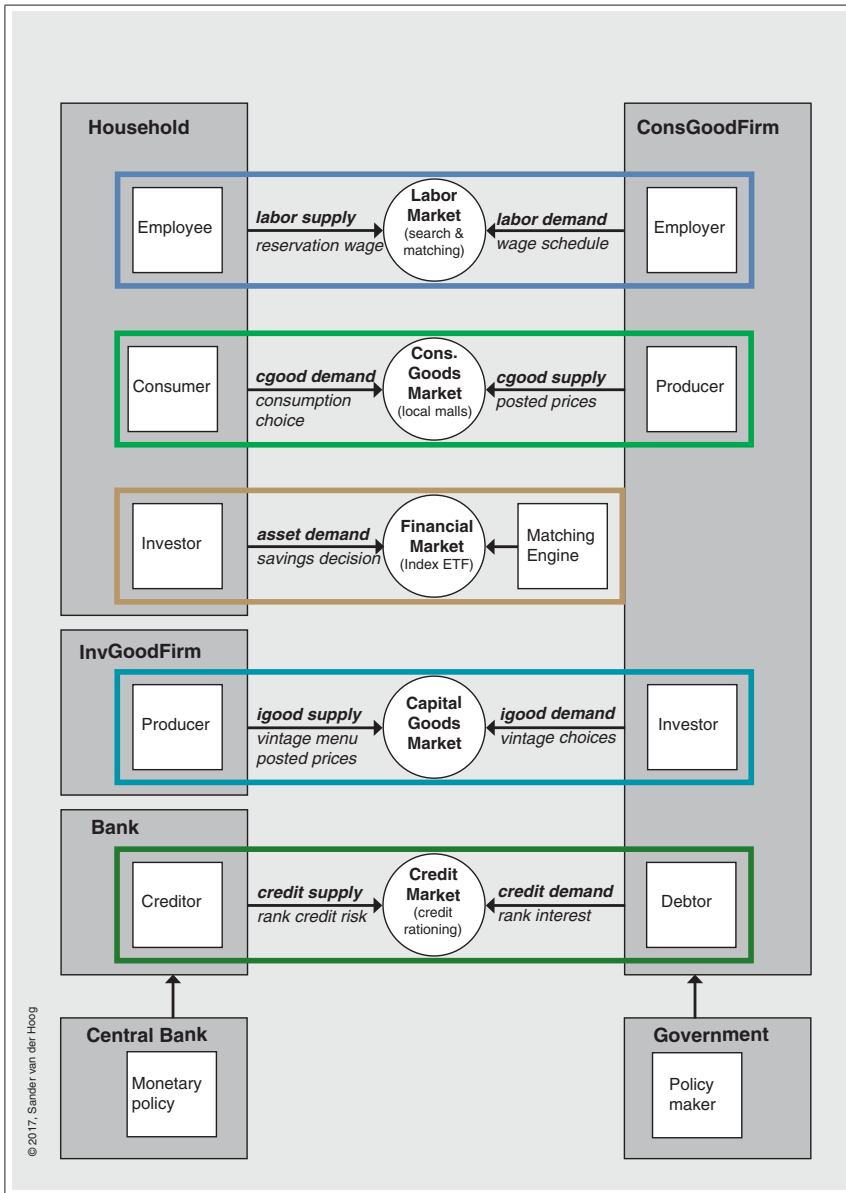
FIGURE 1. Overview of the Eurace@Unibi model.

finance. This can be directly related to their financial fragility and risk of default. In our modeling framework, we simplify this Minskian taxonomy into a dichotomy of financially sound, healthy firms (the hedge financed ones) versus financially unsound, unhealthy firms (the speculative and Ponzi financed ones).

Our model endogenously generates a persistent financial heterogeneity of both banks and firms as the outcome of a dynamic process involving two financial contagion mechanisms, a balance sheet mechanism, and a bank lending mechanism.

The *balance sheet* channel [also known as the broad credit channel in Bernanke and Gertler (1995)] works through the balance sheet of the firm. The firm's financial robustness determines its risk of default and its credit worthiness. Financially healthy firms are able to secure credit if the bank has sufficient liquidity available, whereas financially unhealthy firms are likely to be credit rationed. If the unsound firms default on their loans this affects the balance sheets of the banks through a write-down of bad debt on a fraction of the loans. Once this happens, the bank's equity declines and so does its willingness to lend to other firms. The contagion effect is that all other firms, sound or unsound, now find it more difficult to secure credit.

The *bank lending* channel [also known as the narrow credit channel in Bernanke and Blinder (1988)] depends on the excess liquidity of the bank. Since liquidity is endogenously determined by deposits and withdrawals by firms and households, the bank will restrict lending when it approaches the minimum reserve ratio (a policy parameter). A contagion effect results if a firm with a large liquidity demand has obtained a loan and this restricts the bank's available liquidity such that it will limit the supply of credit to all other firms. Regardless of whether the other firms are healthy or risky, all firms are now more likely to be credit rationed.

Credit market and banking regulations are affecting the magnitude of these two contagion mechanisms. First, a change in the minimum Reserve Requirement Ratio (RRR) affects the bank lending mechanism.[1] A more restrictive reserve ratio makes banks less willing to lend and therefore credit rationing becomes more likely.

Second, the Capital Adequacy Requirement (CAR, or minimum base capital requirement) affects the balance sheet mechanism. A weak capital regulation allows banks to increase their risk exposure and therefore strengthens the financial contagion effect. The contagion does not only apply to firms but also to banks. A higher credit supply to "bad" firms implies that if they default the bad debt will be higher resulting in other banks to bear the brunt of having to write off bad debts as well.

The question how macroeconomic outcomes are affected by these credit regulations evolves around the well-known trade-off between output growth and aggregate volatility. Loose, nonrestrictive regulations tend to lead to higher leverage ratios of both firms and banks. As a consequence, this results in higher growth rates but also leads to more volatility. In other words, there is a positive correlation between debt-led growth and macrofinancial instability, raising the question whether a more restrictive credit policy can induce macrofinancial stability.

On the other hand, more stringent capital requirements restrict banks' risk-taking behavior, resulting in the most risky firms to be credit rationed. A very lax capital requirement allows even the most highly leveraged firms to obtain loans, but now the bank's liquidity reserve requirement could become binding.

If the liquidity constraint is tight, this constraint will ensure financial stability. However, it might also lead to reduced economic growth as the riskier firms now find themselves cut off from liquidity. Hence, there exists a trade-off between growth and stability.

Furthermore, if both constraints are nonrestrictive or lax, the banking sector is allowed to provide a lot of liquidity to the real sector, leading to over-investments in production capacity that are characteristic of a financially fragile boom phase [see, e.g., Delli Gatti and Gallegati (1992)]. This excess production capacity temporarily leads to higher output levels, but in the long run can turn out to be detrimental to financial stability. It should therefore be anticipated that if requirements on reserves and core capital are weak, the risk for severe downturns is particularly large.

Another effect of the nonrestrictive, lax liquidity requirements is that this encourages over-leveraging by the banks, the supply of new loans is high, and the bank takes on more risk. The banks continue to supply new credit to large firms in order to roll-over their debts, crowding out the credit requests of smaller firms that may become illiquid as a result. These illiquidities of healthy firms signals an inefficient allocation of credit resulting from a "congestion" effect on the credit market. Instead, in a scenario with a more restrictive reserve requirement, the unhealthy firms with large credit requests are credit rationed much sooner and become insolvent, while the smaller healthier firms obtain the liquidity they need to produce. The insolvencies indicate that banks are letting the unsound firms exit the market instead of supporting them and crowding out the smaller, healthier firms.

Summarizing, it seems that a prudent regulatory policy should strike a balance between allowing banks to provide sufficient liquidity to any firm that needs it for productive purposes (the safe, healthy, and financially sound firms), while at the same time the banking regulation should prevent banks from refinancing the debts of firms that already have a very high leverage ratio.

A main insight from our analysis is that a tightening of the credit and banking regulations has effects on the most severe downturns, which are defined as the lower percentiles of the distribution of the recession amplitudes. But these effects differ qualitatively between the capital adequacy and the reserve requirement, respectively. In particular, strengthening the capital requirement leads to an increase in the amplitude of the worst downturns (deep depressions), whereas more stringent liquidity constraints induce a reduction of the amplitude of recessions in the lower part of the distribution. Furthermore, these effects appear in a range of regulatory parameters where the median amplitude of recessions is not significantly affected by either of the two variations of the regulatory scheme. Hence, this result is different from a blanket stabilization policy that focusses on smoothing the business cycle, and specifically affects the most severe recessions.

The agent-based approach employed in our analysis allows us to identify in detail the micro-level mechanisms that are responsible for these different implications of the two considered regulatory schemes. Based on this analysis, we obtain a clear intuition about their potential effects on the economic fluctuations and the risks for severe downturns.

The insights obtained by our analysis have clear policy implications since the considered regulatory schemes are at the core of the Basel II/III framework. An argument against the Basel II capital requirements is that they are procyclical. During a downturn, the probability of default (PD) and hence the probability of loan losses increases. This leads to higher demand for collateral and reduces the available capital buffers of banks (their loan-loss reserves). The reduction of the banks' capital buffers limits the banks' capacity to lend in the future and reduces the overall supply of credit, thereby reducing investments and further exacerbating the downturn. These mechanisms are at the center of theories on financial instability, such as the Leverage Cycle [Geanakoplos (2009)] and the Financial Instability Hypothesis [Minsky (1978)]. Our results shed light on the question as to how relevant such mechanisms are in a macroeconomic setting and provide some guidance on how additional regulatory measures might dampen or even amplify such an effect.

The remainder of the paper is organized as follows. In the next section, we discuss different streams of relevant literature. The model is presented in Section 3, and in Section 4, we summarize the main results concerning the effects of two scenarios, namely a tighter CAR and a tighter reserve requirement. The scenarios illustrate the various mechanisms we described above, for a multitude of parametrizations of the model. The results of these two scenarios are then compared to the results of a baseline scenario. Finally, in Section 5, we conclude and offer some suggestions for further research. An online appendix provides a robustness analysis of our main results (Appendix A) and some discussion on the methodology used for measuring the amplitude of recessions (Appendix B) and additional considerations with respect to the effect of credit congestion and zombie lending (Appendix C).

2. RELATED LITERATURE

Our analysis is related to several streams of literature that discuss the linkages between real and financial cycles, the design of stabilization policies as well as the effects of credit market and banking regulations. Below, we briefly review the work that is most closely related to our research agenda and methodological approach.

Business and financial cycles; financial instability hypothesis

Empirical studies how business and financial cycles are interrelated find that recessions after a financial crisis tend to be longer and deeper than other recessions [Claessens et al. (2012)]. Schularick and Taylor (2012) find that a one standard deviation increase in the real growth rate of total private sector debt is associated to an increase in the probability of a financial crisis by approximately 2.8 percentage points.

This evidence suggests that the duration and costs of recessions are determined by the interplay between financial and real variables that tend to be amplified

through a financial accelerator mechanism. The presence of a financial accelerator opens up the possibility of fluctuations to be transmitted through the balance sheets of firms, households, and banks.

We use these findings to investigate whether in our model there are similar relationships between the fluctuations in the credit market and the aggregate real variables. We then relate these to the strength of the policy parameters of the credit regulation in order to investigate whether stronger credit regulations are associated to shorter and more shallow recessions. From a social welfare perspective, the estimated costs of recessions will determine whether strong or weak credit regulations are preferable.

Other empirical studies go beyond viewing the credit market as a mere financial accelerator, and consider credit as an endogenous source of financial disturbances. This is in line with scholars such as Minsky (1978) and Kindleberger (2000) who view endogenously created credit bubbles and the accompanying increase in leverage as a cause of economic instability. Measuring leverage trends along the business cycles may then be a way to monitor the increase in risk of financial crises. In empirical testing of the Financial Instability Hypothesis (FIH), Schularick and Taylor (2012) find that lagged credit growth is the best predictor for future financial instability. This result thus supports the FIH that a credit bubble is a precursor to instability.

Using data for 14 countries, the authors find several trends for the post–WWII era (1945–2008). The data show that an increase in financial instability is mainly caused by three factors: (i) expansion of the role of credit, (ii) higher leverage of banks' balance sheets, and (iii) increased policy intervention preventing a periodic deleveraging.

The first trend is that since 1945 bank loans have increased strongly relative to gross domestic product (GDP), and relative to broad money (M2 or M3). The loan-money ratio grew by 2.19% per year indicating a much stronger dependence on bank credit in the economy.

A second trend is the increased leveraging evidenced by a shift to more risky assets on the balance sheets of banks. The proportion of safe, liquid, low-yield assets has been reduced in favor of more riskier, high-return assets. Since the safe assets can serve as a buffer to financial shocks in "bad times," this shift has weakened the banks' ability to withstand shocks.

The third and final trend is policy intervention. Due to the lessons learned during the Great Depression, policy makers have been more prone to act in financial crises. This has prevented a periodic deleveraging of the financial sector during the post–WWII period, and has implicitly allowed a growth of leverage to occur up to the financial crisis of 2007–8.

Credit market regulations

The new Basel III banking regulation calls for a 4.5 to 7% ratio of core equity tier-1 capital (CET1) to risk-weighted-assets, to be phased-in by 2019 [Basel

Committee on Banking Supervision (2013)]. This long gestation period is to ensure there are no shocks due to a sudden change in regulation. According to Admati and Hellwig (2013), this capital requirement is much too weak, and focusses attention on the wrong issues. They argue that banking regulation is now targeted at banks' assets, while it should be focussed on the banks' liabilities. In particular, banks should have more capital (a lot more) and less short-term debt. More capital would stabilize the financial system and prevent large short-term debt overhangs that cause fire sales of assets in the case of a liquidity crisis. One of the main problems they see is that bank debt is guaranteed by government, which provides the wrong incentives to banks to increase their risk-exposure and to run up their leverage ratios. The capital ratios that Admati and Hellwig advocate are more in the range of 20 to 30% of non-risk-weighted assets, which stands in stark contrast to the current 3 to 4.5% of risk-weighted assets in Basel II and the future 7% in Basel III. Such high capital ratios are also not without historical precedent since in the 19th Century banks funded themselves with 40 to 50% capital. Note, however, that other authors [cf., Calomiris (2013)] have pointed out that such historical comparisons are not entirely unproblematic since banks' equity ratios have changed dramatically over time, and a comparison should take into account the asset risks, as well as changes in institutional arrangements. For instance, in the 19th and early 20th Century banks did not have access to deposit insurance or a safety net such as tax-funded bail-outs.

A related argument deals with the positive impact that very strict banking regulations might have on aggregate economic outcomes. If banks are forced to create buffer stocks of capital, by so-called dynamic loan loss provisioning, this ensures the supply of credit also during times of duress so it will stabilize aggregate output fluctuations.

A third argument considers the social costs of banking crises. A potential counter-argument against higher capital requirements is that this would be very costly and it would reduce the supply of funds available to create loans to firms. Admati and Hellwig argue against this, by showing that the private costs for the banks of having sufficient amounts of equity are much smaller than the social costs of taxpayer-funded bail-out programmes. Also, if banks were to hold more regulatory capital this does not reduce the funds available for lending in any way since every additional dollar or euro in equity capital can be levered up into more lending. So the notion that equity is sitting idle on the balance sheet is in contradiction with accounting principles. Moreover, if banks would hold more regulatory capital this would contribute to financial system stability and improve the general public's confidence in the banking system as well.

Agent-based macroeconomics and policy analysis

A number of recent contributions to the literature have developed closed-economy macroeconomic models using an agent-based approach [e.g., Dosi et al. (2010), Mandel et al. (2010), Dosi et al. (2013), Dawid et al. (2014), Dosi et al. (2015), Dawid et al. (2018a)]. These models incorporate heterogeneity of different

agent types (households, firms, banks) along various relevant dimensions (skill levels, capital stocks, financial variables). Furthermore, the behavior of the agents is modeled with recourse to strong empirical foundations. As discussed extensively, e.g., in Dawid et al. (2018a) and Dosi et al. (2015), many of these models are able to replicate a large set of stylized facts at different levels of aggregation, and can be used to highlight the economic processes that generate these fluctuations. Agent-based macroeconomic models have a number of advantages over more standard macromodels.

Particularly relevant to our purpose is the notion that agent-based models are able to produce self-sustained business cycle fluctuations by relying on the endogenous generation of shocks at the microlevel. This stands in stark contrast to many standard macroeconomic models, such as Real Business Cycle models and Neo-Keynesian models, which require a continuous stream of exogenous shocks to produce business cycle fluctuations.

Particular emphasis on the role of credit markets for aggregate fluctuations is given in Delli Gatti et al. (2003, 2008) and Delli Gatti et al. (2011). An important aspect in their models is that they capture the linkages based on credit relationships between firms and banks, among firms in trade networks, and among banks in interbank networks. These properties allow to gain important insights into the relevant mechanisms responsible for financial contagion effects and to explore the implications of different types of banking and credit market regulations.

Ashraf et al. (2011) also explore the effects of different banking regulations, in a model of shop owners where market interactions are governed by search and matching processes. They study the role of banks both in normal times and in times of crises.

Krug et al. (2015) study the impact of the proposed Basel III regulations in an agent-based model with credit networks. They find that the positive joint impact of several microprudential policies to the resilience of the financial system is larger than the sum of the individual effects measured in isolation, that is, the effects of the policies are nonadditive. This makes the important point that policies should be considered in unison, and it is important to study whether policies are mutually enhancing or detracting.

Another related strain of research is the post-Keynesian literature on stock-flow consistent (SFC) models with endogenous money. For example, Le Heron and Mouakil (2008) describe a SFC model combining the balance sheet and the credit channel in a consistent way, and also Caiani et al. (2016) develop an agent-based stock-flow consistent (AB-SFC) model that is quite similar in spirit to the model we present below.

3. THE MODEL

3.1. Overall Structure

The model describes an economy containing labor, consumption goods, capital goods, financial, and credit markets. The economy is inhabited by numerous instances of different types of agents: firms (consumption goods producers and

capital goods producers), households, and banks. Additionally, there is a single central bank and a government that collects taxes and finances social benefits as well as potentially some economic policy measures. Finally, there is a statistical office (Eurostat) that collects data from all individual agents in the economy and generates aggregate indicators according to standard procedures. These indicators are distributed to the agents in the economy who might use them as input to their decision rules, and are also stored in order to facilitate the analysis of the simulation results. An illustrative overview of the crucial parts of the model is given in Figure 1.

Capital goods of different qualities are provided by capital goods producers with infinite supply. The technological frontier (i.e., the quality of the best currently available capital good) improves over time, where technological change is driven by a stochastic (innovation) process. Firms in the consumption goods sector use capital goods combined with labor input to produce consumption goods. Consumption goods are sold at local market platforms (called malls), where firms store and offer their products and consumers come to buy goods at posted prices (adjusted annually). Labor market interaction is described by a simple multiround search-and-matching procedure where firms post vacancies, unemployed and job-searching households apply, firms make job offers, and, finally, the households either accept or reject. They could reject if their reservation wage is above the wage offer, or if they have received other job offers.

The wages of employees are determined, on the one hand, by the expectation the employer has at the time of hiring about the level of specific skills of the employee, and, on the other hand, by a base wage variable, which is influenced by the (past) tightness of the labor market and determines the overall level of wages paid by a particular employer.

Banks take deposits from all private sector agents (households and firms) and supply loans to the consumption goods producing firms only (i.e., household loans are not currently included). The interest rate a firm pays depends on the financial situation of the firm and the credit volume might be restricted by the bank's liquidity and risk exposure constraints. In case a bank is illiquid, the central bank provides standing facilities through its discount window at a given base rate. It also pays interest on the banks' overnight deposits and might provide fiat money to the government. For simplicity, it is assumed that this is the only form of financing of government debt and that the government does not issue bonds.

Finally, there is a financial market where shares of a single asset are traded, namely an index bond in which all firms in the economy participate (banks, consumption goods firms, and investment goods firms). The dividend per share of the index bond is determined by the aggregate dividend payout of all firms, divided by the number of outstanding shares in the index. This simple representation of a financial market closes the model in the sense that firm profits are channeled back to households and it is also a mechanism to endogenously generate an asymmetric wealth distribution. It captures the important feedback from firm profits to households' wealth, where the fluctuations in dividends only affect the wealth of households owning shares.

The aim of our analysis is to obtain a better understanding of the implications of different types of credit market regulations taking into account the feedback between the investment decisions of firms, their demand for credit, banks' lending behavior, and the overall demand for consumption goods. In order to capture these feedback effects, it is necessary to rely on a model with a representation of the interaction between the economic agents not only on the credit and financial market, but also on the consumption goods, capital goods, and the labor market. Furthermore, as will become apparent in our discussion below, the emergent heterogeneity between firms (and households) plays an important role for the mechanisms that influence the effects of the different regulatory schemes. The Eurace@Unibi model provides a framework to capture these different aspects with the additional property that it reproduces empirical stylized facts on different markets and levels of aggregation [see Dawid et al. (2018a)]. Another advantage of using the Eurace@Unibi framework is that it has already been applied to policy analyses in several other domains, which not only reinforces the confidence that it is a suitable tool for policy evaluation, but also allows us to compare the implications of different policies from various domains and to study their interactions. Based on these considerations, we employ a rather encompassing model for this study, even though the specific focus of our analysis is on the implications of credit market regulations. Hence, the exploration of the underlying mechanisms is mainly concerned with the dynamics of the credit market and the bank-firm credit relationships. In line with this focus, the following model description provides more details on the credit market in order to allow for a more clear understanding of the economic forces driving our results. With respect to the other markets only the main assumptions and modeling choices will be presented due to space restrictions. More extensive discussions of the model specifications for these markets can be found in Dawid et al. (2018b).

3.2. Firm Sequence of Activities

Each firm proceeds through the following sequence of economic activities:

1. On the firm's idiosyncratic activation day,[2] the firm starts its production cycle with production planning. The production plan consists of planned output based on historical observations and the results of market research. Based on the production plan, the firm determines its planned input demand for capital and labor.
2. Financial management of the firm. The firm computes the costs of production and the costs for financing its commitments. If the internal resources are insufficient, the firm tries to finance externally by requesting credit.
3. A credit market with direct firm-to-bank linkages opens. The banks provide credit by servicing loan request from firms on a first-come-first-served basis.[3] The bank decides on the credit conditions for the applying firm (interest rate and amount of credit provided) depending on the firm's financial situation. If the credit request is refused, or not fully accepted, the firm has to reduce its planned production quantity.
4. Bankruptcy of two types could occur. If the firm is credit constrained to such extent that it is not able to pay the financial commitments, it becomes illiquid and illiquidity

bankruptcy is declared. If at the end of the production cycle revenues are so low that the firm has negative net worth, the firm is insolvent and insolvency bankruptcy is declared. In both cases it goes out of business, stops all productive activities, and all employees lose their jobs. The firm writes down a fraction of its debt with all banks with which it has a loan and stays idle for a certain period before it becomes active again.

5. Capital goods market opens. Depending on the amount of financing secured by the firm, it makes physical capital investments. This consists of a vintage choice where the productivity of the capital stock is updated if new vintages are installed.

6. A decentralized labor market opens where firms with open vacancies are matched to unemployed households. The matching is based on the firm's wage offer and on the employee's skill level and reservation wage.

7. Production takes place on the firm's activation day. After production is completed, the output is distributed to local malls. Firms offer goods at posted prices with price revisions occurring once a year.

8. At the end of the production cycle, the firm computes its revenues, and updates its income statement and balance sheet. It pays taxes, dividends, interests, and debt installments. It checks if net worth is negative and if so, declares bankruptcy. Otherwise it continues with the next production cycle.

3.3. Consumption Goods Sector

Consumption goods are produced on the firm's specific activation day, which are uniformly and randomly distributed across the month. The consumption goods are homogeneous regarding quality, but horizontally differentiated and heterogeneous in prices. Each firm conducts a detailed production planning consisting of the calculation of the vertically differentiated input factors capital and labor. Planned production quantities and prices are determined by using estimated residual demand curves obtained from simulated purchase surveys on a test market.[4] In particular, firms set planned production quantities and prices in order to maximize the expected discounted profits over their planing horizon taking into account the estimated marginal costs and the elasticity of demand.

Firms add the produced goods to an inventory held at a mall. Each household visits the mall once a week but not all households visit the mall on the same day of the week. They spend their consumption budget in order to purchase consumption goods. Since the consumption goods are homogeneous regarding the quality but heterogeneous in price, less expensive goods are more likely to be chosen. The decision which good to buy is described using a multinomial logit choice model with a strong empirical foundation in the marketing literature [see, e.g., Malhotra (1984)]. The parameter γ determining the strength of the influence of prices on the consumers product choice is a crucial model parameter in this respect. A large value of γ corresponds to strong price sensitivity of consumers, which implies intensive competition between the consumption good producers. As will be discussed below, such strong competition induces more unstable and volatile economic dynamics compared to a scenario with smaller γ, where firms have more market power and on average gain higher profits.

The households' monthly consumption budget is determined using a linear rule based on the buffer stock theory of savings and consumption [see, e.g., Carroll and Summers (1991), Deaton (1991)]. Households obtain income from wages, unemployment benefits, bank deposit interests, and dividends. They choose their consumption budget according to their average income over a past time-window, which is adjusted upward or downward depending on whether their current wealth is above or below their target wealth/income ratio. Savings are given by the difference between current income and the actual expenditures on consumption, which due to rationing on the consumption goods market might be lower than the consumption budget. For reasons of simplicity, it is assumed that the allocation of households' savings between bank deposits and the purchase of index bonds is random.

Employees are heterogeneous in their general skill levels (general education) and an endogenously evolving specific skill level (job-related knowledge). The specific skill level depends on the technology in use by the firm they work for. The specific skills increase over time during the production process through learning on-the-job. Investments by the firm in new technology vintages impute a new learning phase. Employees learn, that is, they improve their specific skill levels, by using the machinery that is currently employed by the firm [see, e.g., Argote and Epple (1990)]. The speed of learning depends positively on the general skill level of the employee (more general education leads to faster learning and adaptation), and learning only occurs when the productivity of the machinery exceeds the specific skill level of that employee, thus closing the so-called skill-gap.

The production technology in the consumption goods sector is represented by a Leontief production function in which the input factors are used in fixed proportion: one unit of capital is used by one employee. There is complementarity between the productivity of the inputs, that is, the average productivity of the mix of capital vintages currently in use by the firm and the average specific skills of the employees currently employed by the firm. The effective productivity of one unit of capital is the minimum of the productivity of the physical capital and the average productivity of labor.

3.4. Investment Goods Sector

Investment goods[5] are produced by one investment goods producer. The investment goods producer offers different vintages of the investment good with different qualities, where the supply of each vintage is infinite. The introduction time of new vintages with improved quality (higher productivity) follows an exogenous stochastic process. The quality of a machine determines the maximal productivity when used by employees with sufficiently high specific skills. The investment goods producer expands the set of vintages on offer as soon as a new vintage becomes available. In order to simplify the model at this point, the use of input factors by the investment goods producer is not explicitly modeled. Rather, it is assumed that the production of (any vintage of) investment goods is associated

with costs, which increase at the same rate as labor costs. Prices for the vintages are determined by the investment goods producer using a combination of a cost-based approach and a value-based approach [see Nagle et al. (2011)]. More precisely, the investment goods producer estimates the value, in terms of expected discounted future profits, which one unit of the investment good of a certain vintage has for the average firm in the economy. The price of the different vintages is then set as a weighted average between this estimated value and the production costs. In order to close the model, the revenues of the investment goods producer are paid out as dividends to the households.

Consumption goods producers need investment goods as an input factor to their production process. They select a vintage from the list if they want to expand or replace their capital stock. To make a vintage choice, firms estimate the costs and expected future benefits of the different vintages over their planning horizon, depending on the skill distribution of their workforce. The probability to select a certain vintage is then determined by a logit model based on the ratio of the benefit and the costs of each vintage. All vintages depreciate with an identical positive depreciation rate.

3.5. Labor Market

The labor demand is solely determined by the consumption goods producers. If a firm reduces its output, a corresponding number of employees are dismissed such that the new workforce matches the planned output. In case of an expansion of production, the firm posts vacancies that contain wage offers. If the firm cannot fill all of its vacancies due to a tight labor market or due to search frictions, it increases the wage offer to attract more employees. Only unemployed households search for jobs, so there is no on-the-job search. An unemployed household searches actively on average on two randomly chosen days per month. She considers the wage offers of a randomly chosen subset of firms that have posted vacancies and compares these to her reservation wage. If the wage offer exceeds her reservation wage she sends in an application. The maximum number of applications per person per month is fixed exogenously.

For the firm, if the number of applicants is below the number of vacancies, the firm sends job offers to all applicants. If the number of applicants exceeds the number of vacancies, the firm sends job offers to as many applicants as there are vacancies to fill. Firms prefer applicants with higher general skills. Every unemployed household ranks the incoming job offers according to the wage offer, and the highest ranked job offer is accepted. This algorithm is aborted after two iterations, which implies not all firms necessarily fill all their vacancies and/or not all unemployed households find a job. This implies labor market frictions and a possible rationing of firms. In addition, in each period, any employment relationship can be dissolved at random with some small constant probability such that a certain rate of labor turnover is ensured even in the absence of output adjustments by the firms.

TABLE 1. Firm balance sheet

Assets	Liabilities
M_i: Bank deposits	D_i: Bank loans
Inv$_i$: Inventory stock	
K_i: Physical capital	E_i: Equity capital

3.6. Financial Management

At the end of each production cycle (one month), the firm computes its income statement to determine its (accounting) profits. Table 1 shows the balance sheet of the firm. The realized profit of a consumption goods producer equals the sales revenues plus interest received on bank deposits minus the production costs (fixed and variable costs). Hence, $\pi_{i,t}$ is determined at the end of month t as

$$
\begin{aligned}
\pi_{i,t} &= R_{i,t} + r^b M_{i,t} - (C_{i,t}^{\text{Fix}} + C_{i,t}^{\text{Var}}) \\
&= R_{i,t} + r^b M_{i,t} - \left(\sum_{l=1}^{T^L} \frac{p_{t-l}^{\text{inv}} \cdot I_{t-l}}{T^L} + \sum_{l=0}^{T^L} r_{i,t-l}^b L_{i,t-l}^b \right) \\
&\quad - \left(W_{i,t} + \frac{p_t^{\text{inv}} \cdot I_t}{T^L} \right).
\end{aligned}
\tag{1}
$$

For accounting purposes, the costs of investment goods are spread over an amortization period T^L (typically multiple months, $T^L = 18$). For reasons of simplicity, we assume that this amortization period coincides with the duration of the loan taken by the firm in order to finance the investment, such that the cash-flows resulting from the payback of the loan coincide with the monthly accounting costs of the investment. Hence, the fixed costs are the payback installments for all loans for investment expenditures over the previous periods $(t - T^L, \ldots, t - 1)$ and the interest due on loan contracts over the periods $(t - T^L, \ldots, t)$ that includes the loan obtained at the start of this period t. The variable costs consist of the wage bill $W_{i,t}$ and the fraction of total investments that are accounted for in the current month. If profits are positive, the firm pays taxes and dividends according to the rates τ and d, respectively.[6]

3.7. Dividend Payout Policy

Define average net earnings (after-tax profits) over the last n months as $\langle \pi_i \rangle_n = \frac{1}{n} \sum_{s=0}^{n-1} \pi_{i,t-s}$. The monthly dividend payout is based on the average net earnings over the previous 4 months, using the dividend rate d ($d = 70\%$):

$$
\text{Div}_{i,t} = d \cdot \langle \pi_i \rangle_4.
\tag{2}
$$

3.8. Firm Credit Demand

The total liquidity needs to finance the next production cycle consist of the planned production costs, i.e., the new wage bill and planned investments. Besides expenses related to production, the firm also needs to finance the financial commitments that are carried over from the previous production cycle, such as taxes and dividends on profits, debt installments, and interest payments. The total expenditures that need to be financed at the start of the new production period $t + 1$ are as follows:

$$X_{i,t+1} = W_{i,t+1} + p_{i,t+1}^{\text{inv}} \cdot I_{i,t+1} + \tau \max[0, \pi_{i,t}] + \text{Div}_{i,t} + \sum_{l=0}^{T^L} \frac{L_{i,t-l}}{T^L} + \sum_{l=0}^{T^L} r_{i,t-l}^{b} \cdot L_{i,t-l}. \tag{3}$$

The last two terms represent debt installments and interest payments on old loan contracts for the previous periods $(t - T^L, \ldots, t)$ that now need to be serviced. Note that by using this formulation, we allow the firm to obtain a new loan to pay for its taxes and dividends of the previous period. Note also that dividends are paid out of after-tax firm profits, as is usual in the tax code. The demand for bank loans is the remaining part of the total liquidity needs that cannot be financed internally from the payment account (all variables below are determined at the start of period $t + 1$):

$$L_{i,t+1} = \max[0, X_{i,t+1} - M_{i,t+1}]. \tag{4}$$

Firms shop around for credit conditions (the interest rates are variable, the debt repayment period is fixed to 18 months) and request the same amount of credit from a random subset of banks (by default, we let a firm select 2 out of 20 banks at random). Given the credit conditions, the firm then selects the bank with the lowest interest rate offer. Thus, this generates an endogenous network of random credit relationships between banks and firms with some persistence due to the long debt repayment period.

3.9. Firm Liquidity Crisis

Right after its credit market visit, the firm can determine whether it was successful in obtaining all financial liquidity needed for production, interest payments, debt principal, dividends, and taxes. If it was successful, it continues to execute the production plan as scheduled by next visiting the investment goods market to purchase additional physical capital (machinery), and by visiting the labor market, in that order. However, if it was unsuccessful, it now enters into a "liquidity crisis" state. To resolve the liquidity crisis state, the firm tries to rescale its expenditures. Total expenditures in (3) can be simplified to

$$X \equiv P + T + d + D, \tag{5}$$

where X are planned total expenditures, P are production costs, T are taxes, d are dividends, and D are debt commitments. The external financing gap is $F \equiv X - \bar{M}$,

where $\bar{M}$ is the firm's current liquidity (savings account). If the firm was credit rationed, the obtained loans are smaller than the external financing gap, $\bar{L} < F$, so the firm needs to scale back its expenditures such that these can be financed by the available loans and liquidity, i.e., total actual expenditures $\bar{X}$ must satisfy the budget constraint

$$\bar{X} \leq \bar{L} + \bar{M}. \tag{6}$$

We assume the firm rescales its expenditures using a pecking order heuristic, where the expenditure category with the highest priority is to be scaled back first:

1. The firm first sets dividends to zero, $d = 0$, such that X becomes

$$X_1 \equiv P + T + D. \tag{7}$$

   If $X_1 \leq \bar{L} + \bar{M}$, this resolves the liquidity crisis state, and the firm continues to execute its production plan according to the schedule (but with zero dividend payout).
2. If this is not enough, i.e., $X_1 > \bar{L} + \bar{M}$, the firm rescales production costs to P' to satisfy its budget constraint:

$$X_2 \equiv P' + T + D \leq \bar{X}. \tag{8}$$

   This implies $P' \leq \bar{X} - (T + D)$. If the right-hand side is positive then also P' can be chosen positive, and the firm has successfully resolved the liquidity crisis state by (i) rescaling its dividends to zero, and (ii) scaling back production to satisfy the liquidity constraint $\bar{L} + \bar{M}$.
3. If, on the other hand, $\bar{X} - (T + D) < 0$, this would imply negative production costs $P' < 0$ are needed to resolve the liquidity crisis state. Since there is a zero lower bound on the rescaling of the production costs, the firm has insufficient liquidity to service all of its debt commitments even after reducing the production level to zero. In this case, the firm is unable to resolve the liquidity crisis state and defaults on its taxes and debt commitments. This results in the firm's bankruptcy due to illiquidity, with consequences as described in the next section.

3.10. Firm Bankruptcy: Entry and Exit

The occurrence of firm bankruptcy is driven in the model by either an internal or an external cause. The internal cause is that a firm fails on its own account and net worth becomes negative. In this case, we speak of firm insolvency. The external cause is due to credit rationing and we speak of firm illiquidity (as described above in Section 3.9).

– Insolvency bankruptcy: The firm updates its balance sheet and checks for insolvency at the end of the production cycle when it has received the revenues from this month's sales. If the firm equity becomes negative, it is insolvent and goes out of business. It has to perform a debt restructuring before it can continue operations. We resolve the insolvency bankruptcy by rescaling the firm's debt based on the current total asset level, i.e., by means of a debt-equity transformation (see Section 3.11 for details).

– Illiquidity bankruptcy: After visiting the credit market, the firm was unsuccessful in raising all required external funds. It is therefore unable to pay its financial commitments, i.e., taxes, debt instalments, and interests. Firm equity is positive but it does not have enough liquidity to continue operations. It should first raise enough funds to become liquid again. We resolve the illiquidity bankruptcy by rescaling the firm's debt based on the current debt level (see Section 3.11 for details).

The effects of bankruptcy are that a firm fires all employees who then receive unemployment benefits from the government. The firm suspends all production activities for a year. At the end of this idle period, the firm reenters and production is restarted. The physical capital stock remains inside the firm, but is unproductive during the idle period. The local inventory stock is destroyed, representing the economic loss due to bankruptcy. Finally, there is a debt renegotiation with the banks. For each loan, the firm defaults on a fraction and the bad debt should be written off from the bank's balance sheet at which the loan was obtained.

3.11. Debt Deleveraging and Restructuring

Debt deleveraging is modeled by rescaling the total debt. To make it easier for reentering firms to obtain new loans, we should improve their debt-equity ratio and lower their risk of default. This makes it more likely for a bank to accept any future loan requests from such a debt-restructured firm.

In case of an insolvency, the new target debt D^* is set lower than total assets A. The debt rescaling parameter φ is assumed to be constant across all firms and over time:

$$D^* = \varphi A \quad \text{with} \quad 0 \leq \varphi \leq 1. \tag{9}$$

After debt restructuring, the equity of the restructured firm is now positive, $E^* = (1 - \varphi)A > 0$. The debt/equity-ratio after rescaling is given by the constant: $D^*/E^* = \varphi/(1 - \varphi)$.

In the case of illiquidity, the firm does not need to renegotiate its debt per se, since D is already lower then A and equity is still positive. However, since the firm is unable to pay its financial commitments it should raise new funds. It could do so either on the credit market or in the stock market by means of issuing new shares, but since we have precluded firms from issuing new shares (for reasons of simplicity), we also allow illiquid firms to write down part of their debt. In contrast to insolvent firms, illiquid firms do not rescale their debt as a fraction of assets, but as a fraction of the original debt:

$$D^* = \varphi D \quad \text{with} \quad 0 \leq \varphi \leq 1, \tag{10}$$

with new equity given by $E^* = A - \varphi D > E$ and a new debt/equity-ratio $D^*/E^* = \varphi D/(A - \varphi D)$. Since setting a lower value for the debt/equity-ratio improves the firm's chances of getting new loans in the future, the debt rescaling parameter φ must be set to low values $\varphi \leq 0.5$ to ensure that $D^*/E^* \ll D/E$.

3.12. Banking Sector

Commercial banks offer demand deposit accounts (giro payment accounts) and lend to borrowers at varying interest rates. The firms and households select a random bank to deposit their savings and this deposit bank remains fixed for each agent throughout the simulation. Only firms can borrow, and they can initiate a credit relationship with any commercial bank (there is no relationship banking with a house bank). Firms can have more than one loan at a multitude of banks, but a new loan request is always served (partially or in full) by just one bank, when the credit request is successful. It is possible that a new loan request will be partially filled, but then no spillovers of additional loan requests to other banks occur.

The decision whether or not a credit relationship is established is two-sided: Both the firm and the bank have to agree, and the credit conditions will depend on the balance sheet of both firm and bank, subject to capital requirement and liquidity constraints. Both the equity of the bank and the leverage (debt-equity ratio) of the firm enter into the determination of the interest rate.

Over the course of time, a firm may have a heterogeneous debt portfolio with a multitude of banks, each charging a different interest rate. Similarly, the bank's credit relationships evolve over time and it can charge different interest rates to different firms, depending on the financial indicators.

There are three reasons why a bank may stop providing new loans: (i) it has violated its liquidity constraint (the central bank reserve ratio): In this case, it needs to borrow reserves from the Central Bank at an overnight rate. If liquidity is positive, again the bank will automatically redeem its Central Bank debt. (ii) It violates the capital adequacy ratio, with its equity is still positive. The bank is not insolvent, but halt its credit supply. The reason (iii) is similar to reason (ii), but now its equity is negative. This case can occur due to bad debt that is written off. The bank is not declared bankrupt, but the supply of new liquidity to firms is halted. It continues to service the demand deposit accounts (withdrawals and interests) and receives interest and debt installment payments that may lead to a recovery of equity back to positive values.

Bank balance sheet.   The balance sheet of the bank is shown in Table 2. Its assets consist of central bank reserves and outstanding loans to firms. The liabilities are household and firm deposits, and reserve debts to the Central Bank. Banks receive interest and debt instalment payments on their outstanding loans to firms, and pay dividends at a constant rate. They do not purchase shares of other firms or banks. The bank can freely draw advances of central bank reserves from the discount window at the Central Bank, and all banks' reserves are deposited at the Central Bank overnight on which the Central Bank pays the base interest. If the bank has a debt to the Central Bank, it pays the base interest rate to the Central Bank.

The deposit interest rate r^d that the bank pays on demand deposit accounts is lower than the base rate r^{cb}, while the interest rate on loans to firms r_i^b is higher

TABLE 2. Bank balance sheet

Assets	Liabilities
M^b: Reserves	M^b_h: Household deposits
	M^b_i: Firm deposits
L^b_i: Loans to firms	D^b: Central bank debt
	E^b: Equity capital

than the base rate ($r^d < r^{cb} < r^b_i$). This ensures that banks can make a profit. The deposit interest rate r^d is determined as a mark-down on the base rate, while the interest on loans r^b_i depends on the firm-specific balance sheet, in particular, on the Probability of Default (PD). The base rate of the Central Bank is constant by default. It is made endogenous only in case of monetary policy experiments.

Bank accounting.   Bank reserves fluctuate with deposits and withdrawals, interest payments, and finally also with taxes and dividends. The net profits (or losses) after taxes and dividends are added to the reserves and held at the Central Bank. Profits π^b_t at the end of month t are determined by

$$\pi^b_t = \sum_i r^b_i L^b_{it} - r^d \left(\sum_h M^b_{ht} + \sum_i M^b_{it} \right) + r^{cb}(M^b_t - D^b_t), \tag{11}$$

$$M^b_{t+1} = M^b_t + \Delta M^b_{ht} + \Delta M^b_{it}$$
$$+ (1 - \tau) \max[0, \pi^b_t] - d^b(1 - \tau) \max[0, \pi^b_t]. \tag{12}$$

The bank's profits consist of the margin between interests on loans and interests on deposits, plus (minus) any interest paid by (to) the Central Bank on overnight reserves (reserve debt). In case of positive profits, the bank pays taxes and dividends at rates τ and d^b, respectively. The net changes of the demand deposit accounts are given by $\Delta M^b_{h,t} = M^b_{h,t} - M^b_{h,t-1}$ and $\Delta M^b_{it} = M^b_{i,t} - M^b_{i,t-1}$, respectively.

It is possible that due to deposit mutations, the bank's reserves become negative. We assume the Central Bank follows a fully accommodating monetary policy by providing liquidity as needed. The banks thus have a standing facility from which they can draw advances freely. If bank liquidity is positive, the bank automatically pays off its Central Bank debt and receives interest on overnight deposits. If liquidity is negative, the bank automatically draws on Central Bank debt, sets $M^b_{t+1} = 0$ and $D^b_{t+1} > 0$ and pays daily interest to the Central Bank.

Bank credit supply and risk-taking behavior.   The bank's ability to provide credit is restricted by a minimum Capital Adequacy Ratio (CAR) and the minimum Reserve Requirement Ratio (RRR). The bank's risk-taking behavior depends on its current level of exposure to default risk and the capital requirement.

Firms select banks at random in each production period, so the credit market can be viewed as a random matching process. The bank records several characteristics of the applying firms: total debt, size of credit requested, firm equity, and additional

risk exposure. These attributes enter into the risk assessment of the bank and the loan conditions offered to the firm, consisting of size and interest rate for the loan. The firm then selects the bank with the lowest interest rate offer.

On a daily basis, the banks rank their stream of credit requests in ascending order of risk exposure. The least risky credit request of the current day is considered first, but different firms have different activation days during the month, so each new day sees new firms requesting loans to the same bank. If a healthy, financially sound firm requests a loan one day after an unhealthy, financially unsound firm has already obtained a loan with a large risk exposure, the healthy firm may see itself credit rationed due to limits on the banks' risk exposure.

Probability of default.   The firm's PD depends on the creditworthiness of the firm, measured by the debt-to-equity ratio (including the new debt). Following the internal risk-based (IRB) approach of the Basel Accords, there is a minimum risk-weight that sets a floor-level for the PD at 3 basis points (0.03%). We assume a bank associates the following PD to a loan of size L_{it}:[7]

$$\text{PD}_{it} = \max\left[3 \times 10^{-4}, \ 1 - e^{-\nu(D_{it}+L_{it})/E_{it}}\right]. \tag{13}$$

The rule is parametrized by a parameter ν ($\nu = 0.1$) that weighs the impact of the debt-to-equity ratio on the PD.

Credit risk.   We assume there is no collateral for debt, hence debt is unsecured and the expected loss given default (or LGD) is one hundred percent of the loan. Due to this assumption, the credit risk exposure or exposure at default (EAD) is simply the PD times the loan value:

$$\text{EAD}_{it}^b = \text{PD}_{it} \cdot L_{it}. \tag{14}$$

The total risk exposure of the bank is now simply the sum of risk-weighted assets across the entire loan portfolio:

$$\text{RWA}_t^b = \sum_{i=1}^{F} \sum_{k=0}^{K(i)} \text{PD}_{kt} \cdot L_{kt}, \tag{15}$$

where the index i runs over all firms, and index $k = 0, \ldots, K(i)$ over loans of firm i with bank b.

Interest rate rule.   The interest rate offered to a firm is an increasing function of the credit risk reflecting the risk premium that the bank charges to more risky, less financially sound firms. The credit risk posed by firm i enters into the loan conditions as a mark up on the Central Bank base interest rate r^{cb}. The weight of the credit risk in the interest rate can be calibrated by a behavioral parameter λ^B that is the same across all banks ($\lambda^B = 3$). Furthermore, the time-varying operating

costs are captured by a random variable ϵ_t^b, which is uniformly distributed on the unit interval.[8]

$$r_{it}^b = r^{cb} \left(1 + \lambda^B \cdot \mathrm{PD}_{it} + \epsilon_t^b \right), \quad \text{with } \epsilon_t^b \sim U[0, 1]. \tag{16}$$

Capital adequacy requirement. Each bank is required to satisfy a minimal capital adequacy ratio, implying that banks have to observe a limited exposure to default risk. That is, bank equity (core capital) must be greater or equal to a fraction κ of the value of its risk-weighted assets. This assumption is based on Basel II/III capital requirements, where κ is between 4 and 10.5%. The bank's total exposure to credit risk is restricted by $\alpha := \kappa^{-1}$ times the equity of the bank:

$$E_t^b \geq \kappa \cdot \mathrm{RWA}_t^b, \qquad \text{i.e.,} \qquad \mathrm{RWA}_t^b \leq \alpha \cdot E_t^b. \tag{17}$$

Here, E_t^b is bank equity (core capital), RWA_t^b is the value of risk-weighted assets, κ is the capital adequacy ratio, and $\alpha := \kappa^{-1}$ is the maximum leverage in terms of equity to risk-weighted assets. If the constraint is violated, the bank stops providing new loans. Preexisting loans are still administered, firms continue to pay interest and debt installments, and the demand deposits of account holders continue to be serviced. From this, we derive a credit risk exposure "budget" V^b that is still available to fund firms:

$$V_t^b := \alpha \cdot E_t^b - \mathrm{RWA}_t^b. \tag{18}$$

The supply of credit risk in the current period is restricted to this exposure budget V^b. Firm i receives its full credit whenever the bank's total credit risk exposure remains below this limit and is fully rationed when the loan would exceed the risk limit. In terms of the exposure budget V^b, the credit offer reads[9]

$$\bar{\ell}_{it}^b = \begin{cases} L_{it} & \text{if } \mathrm{PD}_{it} \cdot L_{it} \leq V_t^b \\ 0 & \text{if } \mathrm{PD}_{it} \cdot L_{it} > V_t^b. \end{cases} \tag{19}$$

Bank risk exposure is positively correlated to the capital adequacy ratio α. Higher α means more risk is allowed, hence banks have at their disposal a greater budget of excess risk exposure and will tend to give out more risky loans.

Reserve requirement. The banks must observe a minimum RRR, that is, reserves must exceed a fraction $0 \leq \beta \leq 1$ of total deposits of households and firms:

$$M_t^b \geq \beta \cdot \mathrm{Dep}_t^b, \quad \text{where} \quad \mathrm{Dep}_t^b = M_{ht}^b + M_{it}^b. \tag{20}$$

From this an excess liquidity "budget" of the bank is derived as

$$W_t^b := M_t^b - \beta \cdot \mathrm{Dep}_t^b \geq 0. \tag{21}$$

If the excess liquidity budget is sufficient to provide a firm with its requested credit, then it is serviced in full. Otherwise it is *partially* credit rationed such that

the bank attains its minimum reserve requirement. In case of partial rationing, the granted loan size is given by[10]

$$
\ell_{i,t}^b = \begin{cases} \bar{\ell}_{i,t}^b & \text{if } W_t^b \geq \bar{\ell}_{i,t}^b \\ \phi \cdot \bar{\ell}_{i,t}^b & \text{if } 0 \leq W_t^b \leq \bar{\ell}_{i,t}^b \\ 0 & \text{if } W_t^b < 0. \end{cases} \tag{22}
$$

Here, $\bar{\ell}_{i,t}^b$ is the constrained credit demand resulting from applying the CAR-constraint in (19). The fraction ϕ is such that the new reserves (incl. the granted loan) exactly exhausts the RRR constraint:

$$
\{\phi : (M_t^b - \phi \cdot \bar{\ell}_{i,t}^b) - \beta \cdot \text{Dep}_t^b = 0\} \Leftrightarrow \phi = \frac{M_t^b - \beta \cdot \text{Dep}_t^b}{\bar{\ell}_{i,t}^b} = \frac{W_t^b}{\bar{\ell}_{i,t}^b}.
$$

4. RESULTS

4.1. Methodology and Experimental Design

The simulation methodology consists of a Markov Chain Monte Carlo method (MCMC) with batch runs for each parameter setting. Before running the policy simulations, we generate a transient under a stable scenario, in order to have a stable starting point. The transient is ignored in the policy analysis. In the stable benchmark scenario, the parameter $\gamma = 12$ indicates that the competitive pressure on firms in the consumption goods sector is relatively low, i.e., the consumers' price sensitivity wrt. price differences between the firms is low, resulting in high profit margins and low debt. The parameter $\alpha = 10$ indicates that the CAR constraint is nonstringent, and will be nonbinding most of the time. Finally, the parameter $\beta = 0.10$ indicates that the RRR constraint is nonstringent, and will also be nonbinding most of the time.

4.2. Parametrization and Empirical Calibration

The soundness or robustness of financial and nonfinancial institutions can be measured by several financial ratios. A good indicator for the financial robustness is the *equity-asset ratio* which is the opposite of the *leverage ratio*: $E_i/A_i = 1 - D_i/A_i$. For the financial soundness of banks, the *equity-to-risk-weighted-assets ratio* E^b/RWA^b indicates the point at which the CAR becomes binding. When the equity-to-risk ratio falls below the adequacy ratio κ, the constraint is binding, i.e., when $E^b/\text{RWA}^b \leq \kappa$.

In order to obtain a rough empirical calibration for the values of the parameter $\alpha = \kappa^{-1}$ in the CAR, we use an empirical study by Hanson et al. (2011, p.39), in which empirical data on the E/A-ratio of US banks are provided. Historical values for the period 1840–2009 are shown to vary between 4 and 55%, and for the period 1976–2009 values varied between 4 an 14%. For the period 1996–2009,

TABLE 3. Parameter sensitivity analysis (default values are in boldface)

$\alpha \in A$	1	2	4	6	**8**	10	12	16	24	32
$\beta \in B$	0	0.01	0.02	0.05	**0.10**	0.20	0.50	0.90	0.99	1.00
$\gamma \in C$	12	14	**18**	18.5	19	19.5	20	22	24	26
r^{cb}	0	0.001	0.0025	0.005	0.0075	**0.01**	0.02	0.03	0.04	0.05

the equity-to-risk-weighted-assets ratio of US banks varied between 8 and 20%, which corresponds in our model to $\alpha = 12.5$ and $\alpha = 5$, respectively.

To convert the equity-to-total-assets ratio into the equity-to-risk-weighted-assets ratio, a rule of thumb is to multiply by two, assuming the average risk weight is 0.5 [Ratnovski (2013, p.66)]. Hence, a 4% equity-to-total-assets ratio corresponds to 8% equity-to-risk-weighted-assets, and $\alpha = 12.5$ in our model. And a 55% equity-to-total-assets ratio corresponds to a 110% equity-to-risk-weighted-assets, or $\alpha = 0.9$ (i.e., risk-weighted assets covered by more than 100% of equity). Therefore, the empirical range for the α-values lies between 1 and 12.5.

The Basel Committee on Banking Supervision (BCBS) has proposed the following Basel III phase-in arrangements from 2013 to 2019 [Basel Committee on Banking Supervision (2013)]. The Minimum Common Equity Capital Ratio is 4.5%, i.e., the CET1 should be 4.5% of the value of risk-weighted assets. In addition, there is the mandatory Capital Conservation Buffer of 2.5%, totaling 7% of common equity capital. The minimum total capital ratio is 8%, consisting of Tier-1 and Tier-2 capital. On top of that, the national regulatory authorities are allowed to levy a discretionary Countercyclical Buffer on Globally Systemically Important Banks, the so-called G-SIBs, of between 1 and 2.5% (totaling 10.5% of CET-1 capital).

For the parameter values of α, these percentages 4.5, 7, 8, and 10.5 correspond to $\alpha = 22$, 14.4, 12.5, and 9.5, respectively. The theoretically proposed range of α therefore lies between 9.5 and 22. To take into account both the empirical data and the Basel III regulatory scheme as proposed by the BCBS for 2019, we calibrated our simulations to α-values lying between 2 and 32.

To obtain an empirical calibration for the values of the parameter β in the reserve requirement, we use the current values as set by the Central Banks around the world. In Canada, Australia, New Zealand, the United Kingdom, and Sweden, there is no reserve requirement, while in China it is 19.5% (as of Feb. 2015). In the United States, it can be 0, 3, or 10%, depending on the net transaction accounts at the depository institution. For the Eurozone, the reserve requirement is 1%. Finally, there is the Chicago Plan for Monetary Reform [Douglas et al. (1939)], in which the authors call for a 100% reserve requirement.

In order to do justice to this wide range of variability, we did not calibrate the value of β, but instead used the full range of values between 0 and 100%. The parameter settings in Table 3 are the combinations used for the policy analysis,

varying from nonbinding to strongly-binding capital and liquidity constraints, respectively. With $\alpha \in A$, $\beta \in B$, we explore a 10×10-grid.[11] The parameters $\gamma = 18$ and $r^{cb} = 0.01$ are our default values under the unstable scenario (see below), and are fixed throughout. We have performed robustness tests with respect to the values mentioned in Table 3.

4.3. Baseline Scenario

After running the stable benchmark scenario for generating the initial state of the economy, we now vary the policy parameters to generate various unstable economies. This is achieved by increasing the consumer price sensitivity parameter from $\gamma = 12$ to $\gamma = 18$, that is, by increasing the competitive pressure on the firms which will reduce their profit margins.

In the *baseline scenario*, both CAR and RRR constraints are weak, using the following parameter settings: $\alpha = 8$, that is, the banks' core capital should be at least 12.5% of risk-weighted assets, and $\beta = 0.10$, that is, there is a 10% central bank reserve requirement.

Scenario description.   Figure 2 shows the correlation between the business cycle and the financial cycle in the model. The figure illustrates the classic Minskian mechanism of a risky boom, i.e., during the upswing of the business cycle leverage and financial fragility increase, while during a downturn the opposite occurs [Minsky (1978, 1986)]. This also corresponds to the mechanism identified by Geanakoplos (2009) as the Leverage Cycle, which explains the increase in financial fragility in terms of collateral constraints.

The figure shows that financial fragility is synchronized with the business cycle. During the boom phases I, II, and III, the firms' leverage rate increases, indicated by a decrease in the average equity/asset ratio, showing signs of increased fragility. Recession phases between I and II, and between II and III are deleveraging, with an increase in the average equity/asset ratio, which indicates an improvement in financial robustness. During the recovery stage (phase II) the financial fragility increases again, only to be followed by another fragile boom phase. In general, not all boom phases need to be fragile and associated with increased leverage. Similarly, not all recessions need to be deleveraging. Note that at the end of the boom phase I, at the turning point, the average equity/asset-ratio continues to decrease for a while. This is also the case after the second boom phase II, and is most likely due to a debt overhang which causes the financial fragility to have some inertia.

To uncover the main mechanisms underlying this macroscopic result, we show microeconomic—or mesoeconomic—variables, averaged across the corporate and banking sectors. In Figure 3, we show plots for selected variables of the corporate sector: total output, firm capital stock, firm profits, and total firm debt, aggregated across small or large firms, respectively. Large (small) firms are defined as having a capital stock that is above (below) the mean capital stock. In Figure 4, we
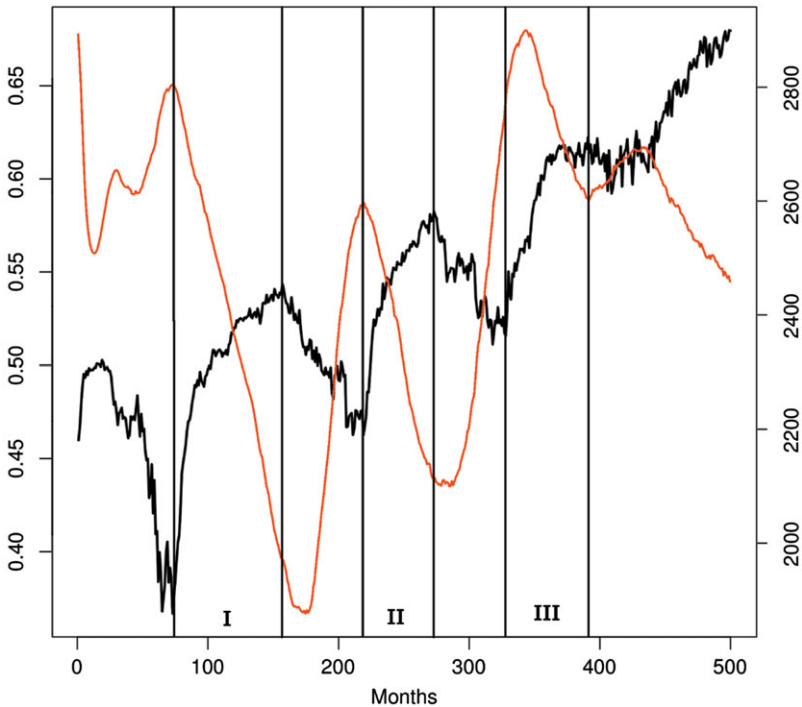
FIGURE 2. Mechanism of the financial instability hypothesis. Parameters: $\alpha = 8$, $\beta = 0.50$, $\gamma = 18$.

show the number of active banks (i.e., not insolvent or having binding equity or liquidity constraints), and the number of inactive firms (these are either insolvent or illiquid), disaggregated into small and large firms.

1. *Expansion of output.* We start with equal amounts of large and small firms, defined with respect to the mean capital stock: Small (large) firms have a capital stock below (above) the mean capital stock, respectively. However, this quickly bifurcates into many small firms and a few large firms.

   From the start, the large firms have a slightly higher capital stock and a higher capacity utilization rate [Figures 3(c) and (d)]. Hence, the large firms have higher output per firm and also invest more to expand their production capacities. At the same time, due to the high competitive pressure, their profit margins are low and some large firms are also generating negative profits [Figure 3(b), black curve], so they need debt to finance their investments [Figure 3(e)]. The investments per firm are substantially higher than those of small firms, who do not invest that much [Figure 3(c), red curve].

2. *Financial variables.* How are firms able to finance their investments? Since profits are negative and declining, they need new credit to roll-over the
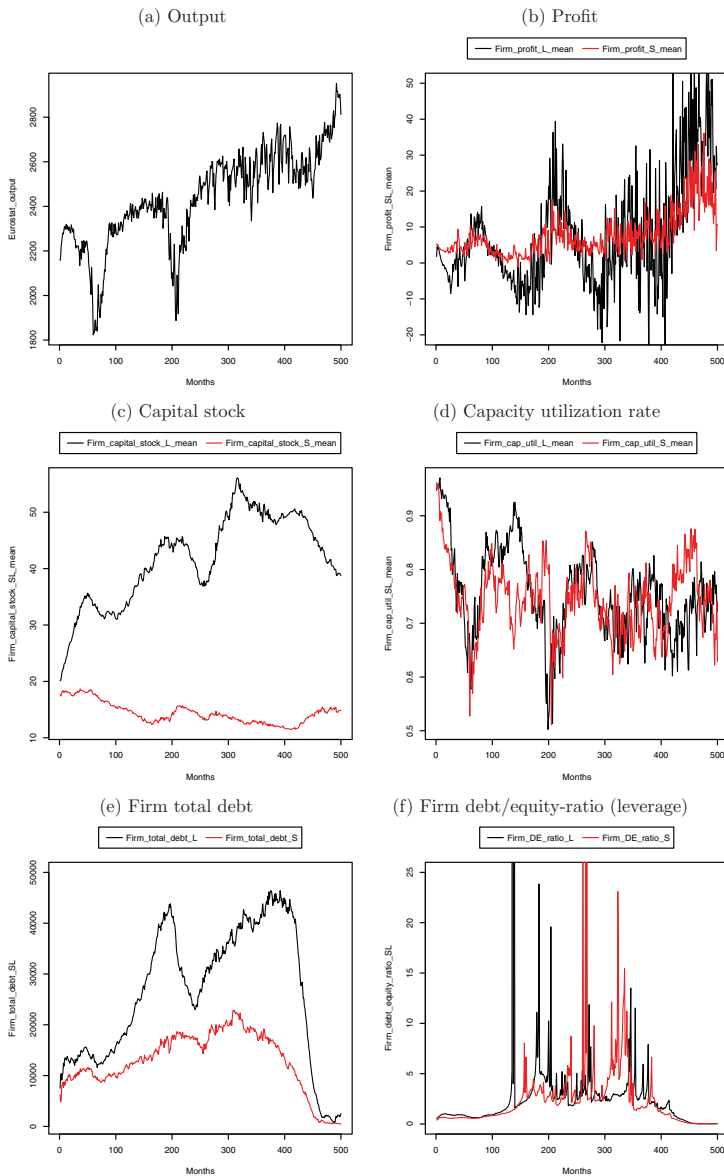
(a) Output

(b) Profit

(c) Capital stock

(d) Capacity utilization rate

(e) Firm total debt

(f) Firm debt/equity-ratio (leverage)

FIGURE 3. Baseline scenario. Parameter values: $\alpha = 8$, $\beta = 0.10$, $\gamma = 18$. We show a comparison between small and large firms (small = red, large = black lines). Large (small) firms are defined as having a capital stock that is above (below) the mean capital stock. (a) Total output. (b) Mean profit. (c) Mean capital stock in units. (d) Mean capacity utilization rate (percent). (e) Total firm debt. (f) Firm debt/equity-ratio (leverage). This figure shows how the large firms are for the most part responsible for the debt bubble since they are the first to build up leverage and debt. Two debt bubbles are visible. The first crash comes after large firms deleverage, the second as small firms deleverage.
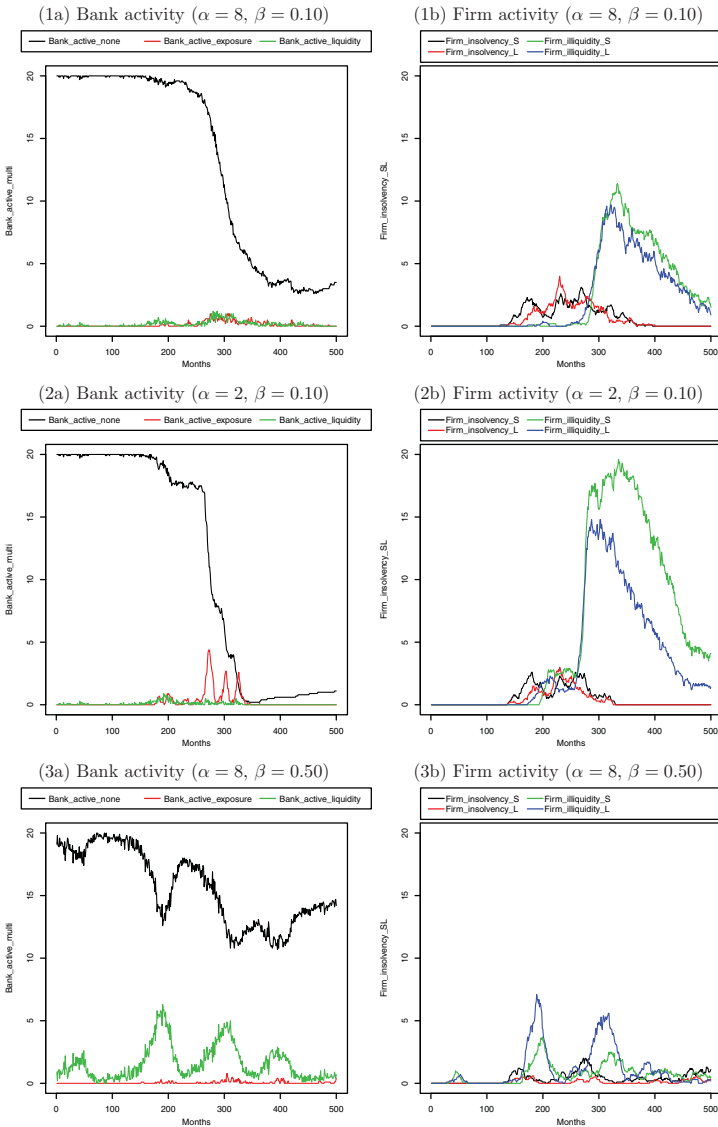
FIGURE 4. Panel 1: Baseline scenario, parameter values: $\alpha = 8$, $\beta = 0.10$. Panel 2: Scenario for capital adequacy constraint, parameter values: $\alpha = 2$, $\beta = 0.10$. Panel 3: Scenario for the minimum reserve requirement, parameter values: $\alpha = 8$, $\beta = 0.50$. Plots (a): Bank activity. Banks can become inactive due to three reasons: negative net worth (insolvency), an active CAR constraint, or an active RRR constraint. The green curves indicate the number of banks that become inactive due to a binding liquidity constraint. The red curves indicate the number of banks that become inactive due to a binding capital adequacy constraint. Plots (b): Firm activity, showing the number of firms that become insolvent or illiquid, disaggregated into large a small firms (defined as capital units above/below the average capital stock).

old debt. The leverage rate, as measured by the debt-equity ratio, is higher for large firms than for small firms, indicating that they are more fragile. The booms typically display an increase in leverage by the large firms [Figure 3(f), black curve], as they must invest to expand their production capacity [Figure 3(c)]. So this is an economically, profit-driven dynamic leading to over-investment.

3. *Credit bubble.* Along the credit bubble, the average debt of large firms builds up much quicker than the debt of small firms [Figure 3(e)]. The financial robustness of firms is pro-cyclical; it decreases during recessions and increases during boom phases (as in Figure 2, phase I).

4. *Capacity utilization in relation to investments.* The capacity utilization rate [Figure 3(d)] is also procyclical and is leading the business cycle by several months, which corresponds to empirical findings in Stock and Watson (1999). During a recession, firms make more use of their existing capital stock rather than investing in new capital goods. The utilization rate reaches its maximum during the boom and already starts to decline well before the downturn occurs, making it a good indicator for business cycle turning points. During the boom phase investments are high, but the utilization rate already starts to decline due to a slowdown in output, followed by a decline in investments. This is an indication of over-capacities building up during the boom stage of the cycle. When the boom stage is finally over and the cycle has reached its top, the utilization rate is already at a minimum (around 50%), investment declines, and financial robustness is at a minimum, i.e., financial fragility is at maximum (Figure 2, between phase I and II).

5. *Banks.* Due to the nonrestrictive capital constraint (in this baseline scenario), the banks support financially sound firms as well as unhealthy firms for a long period of time. This yields a higher level of exposure to credit default risk during booms since the supply of credit is linked to bank equity and therefore procyclical. Banks become inactive only gradually [Figure 4(1a)], because the capital constraint is slack. In Figure 4(1a), the red line indicates the number of banks that become inactive due to a binding capital constraint. The green line indicates the number of banks that become inactive due to a binding liquidity constraint. Eventually, the liquidity constraint becomes binding for some banks because large firms' credit demand increases over time.

6. As a result of this broad supply of liquidity, a considerable number of large and unsound firms continue to produce and receive roll-over credit to finance their debt, exhibited by an unstable debt bubble [Figure 3(e), black line]. The number of active firms, however, remains at an artificially high level [Figure 4(1b)], since large firms that are actually insolvent and that should have been credit rationed much earlier—if the constraint had been more restrictive—are kept alive almost artificially by the banks. We identify such unsound firms as Zombie-firms à la [Caballero et al. (2008)]. In this case, the illiquidities are being caused by a binding liquidity constraint of the

bank around period $t = 300$. In Figure 4(1a), the green curve indicates the number of banks with binding liquidity constraint, and in Figure 4(1b), the blue and green curves indicate the number of illiquid small and large firms, respectively.

7. *Credit crunch and rebound.* The moment the liquidity constraint becomes active, the new credit to large firms is declining. There is a sudden deleveraging by large firms, shown by a sudden increase in the average equity-asset ratio (the inverse of the asset-equity ratio, and an indicator for financial robustness). At the same time, their profits improve, since investments and hence debts decline. The large firms can increase their output by increasing their capacity utilization rate instead.

   The debt restructuring does not affect the capital stock, so after the unhealthy firms have successfully written down some of their debt, they come back with the same production capacity and start again to expand. This results in another round of leveraging, a new credit bubble is building up [Figure 3(e), black line, $t = 250$–300], and this is associated to a decreasing E/A-ratio. Also, profits are steeply declining while investments increase. As a result, there is a long-term dependency in the number of illiquid firms, even long after the credit crunch [Figure 4(1b)].

8. *Comparison of small and large firms.* Throughout the entire episode, the small firms do not expand their production capacity and have constant output. Because of their low rate of investments their capital stock even declines [Figure 3(c)]. On the financial side, the small firms have positive or slightly negative profits [Figure 3(b)] and their financial robustness is better than that of the large firms. However, also small firms may build up leverage, as shown by the debt-equity ratio [Figure 3(f), red curve].

4.4. Policy Analysis

How can the credit crunch and the associated downturn as illustrated above be avoided? The discussion of the mechanisms leading to the observed downturn suggests that the easy access to credit for financially unsound firms plays an important role in the generation of the credit bubble and the subsequent credit crunch. Hence, the question arises in how far restricting the credit supply helps to avoid the emergence of such downturns. To address this question, we examine how a tightening of the CAR respectively the RRR affects the economic dynamics. In online Appendix C, we provide a more detailed discussion of the transmission channels associated to these two policies.

   We follow the empirical literature on the relationship between financial cycles and business cycles to select the relevant indicators for measuring a positive policy effect [c.f. Claessens et al. (2012), Schularick and Taylor (2012), Jordà et al. (2013), Jordà et al. (2015)]. In particular, we consider the amplitude and cumulative loss of output during a recession as an indicator for the economic losses associated to such severe downturns. The amplitude of a recession is measured in units of

output, from the top of the boom phase to the trough of the downturn (see online Appendix B for details). The cumulative loss is measured as the output that is not being produced during the entire duration of the recession, by combining the amplitude and the duration measure.[12]

In line with our main motivation for this study, we are especially interested in the effects of the different policies on the lower part of the distribution of these measures, i.e., on the severity and probability of the most extreme downturns.

Tightening the capital adequacy requirement.   In Figure 5(b), we report results for the amplitude of recessions, under different scenarios with respect to the CAR. The box plots show the distribution of all amplitude values for all recessions that occur, pooled across 20 simulation runs (one run contains on average 5–10 recessions, so the number of observations lies between 100 and 200 recessions per box plot).

The considered range for α-values is from 1 to 32. The current capital adequacy ratio in Basel II is $\kappa = 4\%$, corresponding to $\alpha = 25$. The minimal core capital requirement proposed in Basel III is set at $\kappa = 7\%$, which corresponds to $\alpha \approx 14$, whereas the value $\kappa = 10.5\%$ ($\alpha \approx 9$) holds if all regulatory requirements including the discretionary countercyclical capital buffers for SIFIs are taken into account.

The box plots in Figure 5(b) show that for the maximal value of $\alpha = 32$ (3% regulatory capital) the bottom whisker indicates that 95% of recessions have amplitudes between 0 and $-1,900$ units of output lost. A more restrictive CAR implies lower values of α and this corresponds to an increase in the amplitude of recessions, at least until one reaches $\alpha = 4$, which corresponds to a capital adequacy ratio of $\kappa = 25\%$ and is still within the range proposed by Admati and Hellwig (2013). The extremely low values of $\alpha = 1$ and $\alpha = 2$ correspond to $\kappa = 100\%$ and $\kappa = 50\%$, respectively, which are theoretically feasible, but implausible values in practice. A capital adequacy ratio of 100% would surely make the economy very stable and reduce the amplitude of severe downturns, which is also seen in the box plots, but this level is politically unattainable.

To understand in more detail the mechanisms underlying this observation, we consider the dynamics in a scenario with a very restrictive CAR, namely $\alpha = 2.0$ ($\kappa = 50\%$) and $\beta = 0.10$. We emphasize that this is not meant to be a realistic value, but is used to clearly illustrate the dynamics at work. This scenario shows exactly what happens during a credit crunch when all banks stop lending. The main driving mechanism behind the economic collapse is the slow build-up of debt in unhealthy firms that increases the risk exposure of banks. A strict capital constraint causes a sudden collapse, instead of a more gradual deleveraging of debt. This sudden collapse then gets transmitted to the real sector. In Figures 4(2a) and (2b), we illustrate the main mechanisms underlying such effects of a tight CAR constraint.

1. *Build-up.* The nonbinding, weak liquidity constraint has flushed the credit market with liquidity, so that total credit develops into a bubble. At the start, many firms
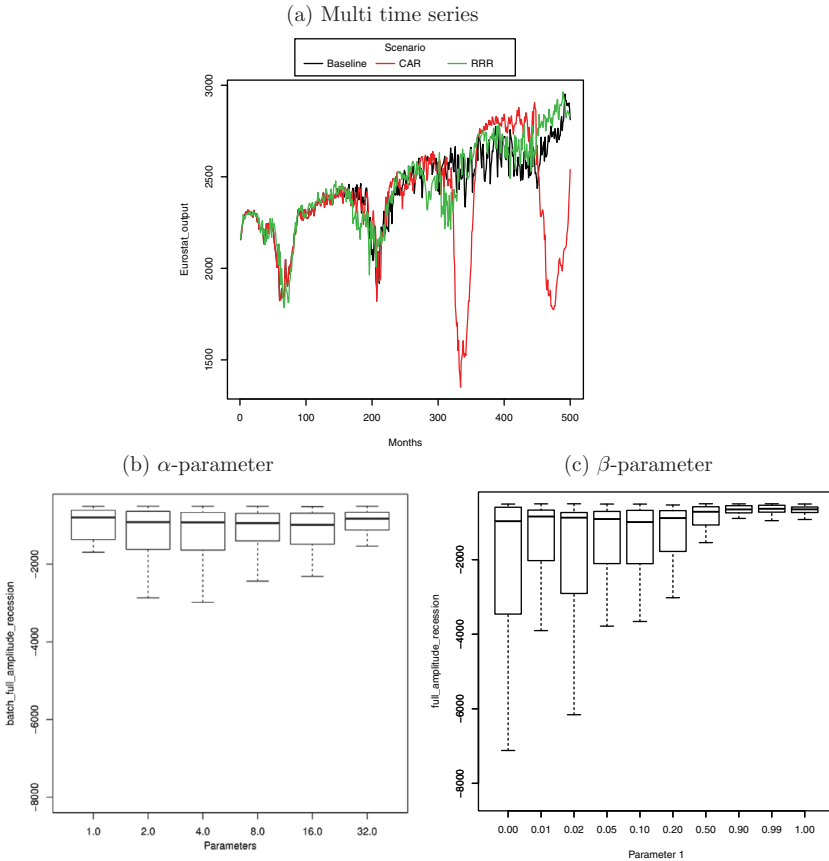
(a) Multi time series

(b) α-parameter

(c) β-parameter

FIGURE 5. Top Panel: Time series plot of total output for three scenarios: Baseline ($\alpha = 8.0$, $\beta = 0.10$), restrictive Capital Adequacy Requirement (CAR) ($\alpha = 2.0$, $\beta = 0.10$), and restrictive Reserve Requirement Ratio (RRR) ($\alpha = 8.0$, $\beta = 0.50$). To be able to show deep recessions, we show results for a single run since averaging across multiple runs would destroy the deep downturns. Bottom Panels: Box plots of the amplitude of recessions for different values of α and β. Amplitude is measured as the total loss in output, from the peak of a boom to the through of a recession. For each parameter value, the box plot shows the distribution of all recessions across 20 batch runs, for simulations of 500 months. (b) Parameter sensitivity analysis wrt. the α-parameter related to the CAR. Fixed: $\beta = 0.10$. The relation between α and the amplitude of recessions is convex: for very low and very high α-values the amplitude is small, while for intermediary values it increases. However, within the range proposed by the Basel III regulations ($4.5\% < \kappa < 10.5\%$, or $9.5 < \alpha < 22$), a more restrictive CAR corresponds to increasing amplitudes of recessions. (c) Parameter sensitivity analysis wrt. the β-parameter for the RRR. Fixed: $\alpha = 9.5$ ($\kappa = 10.5\%$ as in Basel III). A more restrictive RRR (higher β-values) corresponds to decreasing amplitudes of recessions.

are increasing their debt to finance production and financial commitments. As in the baseline scenario, the large firms have large liquidity needs, so they cause the banks to build up large risk exposures. But since in this scenario the CAR constraint is more strict, they hit it more often. This tougher constraint shields a small number of banks from becoming insolvent, although they do become inactive due to a binding CAR [Figure 4(2a), red curve]. These banks could become active again later on.

2. *Credit crunch.* Once banks have stopped lending, any excess central bank reserves that are held-up in these banks are no longer available as collateral on the RHS of the RRR constraint, which makes them "unproductive." If other banks would hold these excess reserves they could expand the liquidity supply by leveraging up these reserves. So in this respect, the excess reserves in inactive banks are unproductive.

    This affects the unhealthy firms the most since they have lower E/A-ratios (higher D/E ratios) which puts them at the bottom of the risk-ranking in the banks. Hence, the large firms are more likely to be credit rationed and the number of illiquid large firms increases in comparison to the baseline scenario. However, also the small firms are harmed due to the consequent credit crunch [Figure 4(2b)].

3. *Insolvency of bad firms.* The economic breakdown occurs in two stages. The first stage is characterized by unhealthy (Ponzi) firms becoming insolvent [Figure 4(2b), the black and red curves indicate insolvent firms]. The insolvencies of bad firms are not harmful in the beginning, but as bad firms have higher debt, they will default on larger loans as well, affecting the banks' balance sheets through the equity channel (the narrow bank lending channel).

4. *Bank equity.* The continued insolvencies of these firms cause a slow deterioration of bank equity, resulting in some banks becoming inactive [Figure 4(2a)]. This affects the banks' ability to provide new loans, as the budget for risk exposure is diminished. The more restrictive CAR implies that the turning point in the bank equity bubble comes earlier, hence the credit crunch starts earlier.

5. *Active capital constraint.* When the equity of a majority of banks has eroded sufficiently, the capital constraint becomes active. The plot of bank activity [Figure 4(2a)] illustrates well that the first constraint to become binding is the capital constraint (the red line indicates the number of banks that have become inactive due to a binding CAR constraint). Note that the total number of inactive banks includes banks that are insolvent, as well as banks that have either the CAR or RRR constraint binding. At the same time, a small number of banks stop lending due to negative equity, and the first wave of illiquid firms ensues around period 180 [Figure 4(2b)].

6. *Credit crunch.* In the second stage, it is the refinancing of debt by the Ponzi firms that are not yet insolvent but that require liquidity to keep them afloat which is going to bring about a collapse in output [Figure 5(a), red curve]. First, the disappearance of bad firms reduces total output since they go out of business.

7. *Large firms rescale production.* Second, the bad firms that do remain in business cannot get any credit for production or to service debt. Since priority is given to debt servicing, they must rescale production. Thus, the collapse in output is the combination of a production stop by the inactive firms and the reduction in output by the active firms.

8. *Bad firm illiquidity.* There is a large number of synchronous illiquidities of Ponzi firms, since the bank gives priority to healthy firms and rations the credit to unhealthy firms [Figure 4(2b)]. This can affect both small (S) or large (L) firms. What happens

to these illiquid firms? During the bankruptcy procedure, these firms are restructuring their debt, so they return, after 12 months, as healthy firms in the population. However, as soon as the capital constraint of the bank ceases to be restrictive (i.e., the bank's risk exposure is reduced due to the debt restructuring of the illiquid firms), the number of Ponzi financed firms starts to increase again and another debt bubble is formed.

9. *Banks inactive.* This causes further damage to the bank balance sheets and as soon as equity is negative or the maximum exposure limit is reached, the bank stops providing loans to firms altogether. This reduces many banks to the inactive status due to negative net worth and results in an overall credit crunch [Figure 4(2a)]. The banks' excess liquidity is still positive, so the banks could lend from a liquidity point of view, but their regulatory core capital does not allow it.

10. *Restarting the credit bubble.* Because there is no restriction on liquidity, the debt bubble will restart after the capital constraint has relaxed again.

It is important to note that the liquidity constraint (RRR) in this case hardly ever becomes binding, as the value of β is too low. This can be verified in Figure 4(2a) (green curve), which indicates the number of banks that become inactive due to a binding liquidity constraint. Note that at the moment of the credit crunch, around period 275, the number of illiquid small firms is higher than the number of illiquid large firms, which is an indication of an indirect contagion effect through the banking system which we could call the Zombie-effect [see Caballero et al. (2008)]. The Zombie-effect is the notion that a small number of unhealthy firms with a high risk profile hamper the ability of banks to provide liquidity to other, more healthy firms. After the unhealthy firms have been allowed to grow and subsequently become insolvent and write off their debt, the banks' equity is depressed to such a degree that they cannot supply any credit to any other firms. It is therefore in the interest of these banks to keep the bad firms alive as long as possible, hence the name Zombie-firms. In addition, there continue to be firm illiquidities for a long period of time after the sudden wave of illiquidities. Another important effect is the large concentration in the banking sector: After period 325, only two or three banks remain active [Figure 4(2a)].

The (dis)advantage of strict capital policies.   After having seen these results, we might ask: Is there any advantage to having a strict CAR? Risky firms are restricted from obtaining large debts, so that as the debt bubble breaks banks are less affected. The sudden effectiveness of the capital constraint causes more banks to survive, but it does not prevent the surge of firm illiquidities that follow the credit crunch.

The disadvantage of a strict capital policy is that after the CAR constraint is no longer binding, the surviving banks have high liquid resources that are now used to start another credit bubble. Since there has been a wash-out of the competition and a concentration in the banking system, the remaining banks now gain more profits and can maintain the credit bubble for longer. The bad firms can again obtain financing, output recovers quickly, but in the meantime, the average debt of unsound firms is building up to greater heights than during the original bubble.

In conclusion, a more stringent CAR constraint does not solve the underlying problem that banks are running up their risk exposure and that financially unsound firms are receiving too much credit. To solve this, a combination of the capital adequacy ratio and the liquidity constraint seems needed.

In the next scenario, the restrictive capital constraint is replaced by a restrictive liquidity constraint. Instead of breaking the credit bubble the intent is now to prevent the bubble from growing in the first place.

Tightening the reserve requirement.   In Figure 5(c), we report results for the amplitude of recessions, under different scenarios with respect to the RRR constraint (varying the parameter β). As above, the box plots show the distribution of all amplitude values for all recessions that occur, pooled across 20 simulation runs. The considered values of β span the entire range from 0 to 100% reserve requirement, and a more restrictive RRR corresponds to higher β-values. For the α-value, we have considered here the most restrictive case of Basel III, namely $\alpha = 9.5$ ($\kappa = 10.5\%$). From the box plots it becomes clear that a more restrictive RRR is associated to a decrease in the amplitude of recessions. In the online Appendix A, we also provide a robustness analysis confirming the qualitative insight that increasing β tends to significantly reduce the amplitude of recessions, whereas reducing α has no systematic positive effect in this respect.

To explore this scenario in more detail, we consider the dynamics under the parameter setting $\alpha = 8$ and $\beta = 0.5$, corresponding to a restrictive 50% reserve requirement but a nonrestrictive capital adequacy ratio of 12.5%. In Figures 4(3a) and (3b), we illustrate the main mechanisms for this scenario.

1. *Liquidity constraint binding.* The bank gives credit up to its constraint which then becomes binding [Figure 4(3a), green curve]. As the liquidity constraint is binding, the capital constraint is not binding [Figure 4(3a), red curve]. In case a bank is illiquid, it draws advances from the Central Bank and remains active. This means banks with a binding liquidity constraint all remain active and equity remains positive. Since the credit demand of large unsound firms is typically larger than that of small firms—the replacement investments are typically larger when the firm has a larger capital stock, and total debt is larger in order to finance the investments— the former are more often credit rationed than the latter. This causes large firms to enter into illiquidity bankruptcy at an earlier stage and not all at the same time [Figure 4(3b), blue curve].

2. *Waves of illiquidity instead of one big surge of illiquid firms.* Because the liquidity constraint remains binding, firms are becoming insolvent and illiquid during the entire second half of the simulation [Figure 4(3b), all colored curves]. The bad debt is spread out over time and does not harm the banking sector that much, allowing it to be absorbed by the banking system and banks become inactive more gradually [Figure 4(3a), black curve].

3. *Schumpeterian cleansing effect.* The banks continue to provide loans, hence after the wash-out of financially unsound large firms that became illiquid [Figure 4(3b), periods 200 and 300], a new credit bubble is formed and total credit to firms is increasing again. This could be attributed to the so-called *cleansing effect* of

recessions à la Schumpeter, in which bad firms are allowed to fail in favor of more healthy, surviving firms.

4. *Bank exposure and leverage.* Total bank exposure and leverage is lower in the case of the restrictive liquidity constraint exactly due to the absence of a credit crunch. Moreover, this total exposure is distributed among many more banks hence the banking system as a whole is more robust against the failure of a single, large firm.

Advantage of the nonrestrictive reserve requirement. If there is no restraint on lending this encourages over-leveraging by the banks, the supply of new loans is high, and the bank takes on more risk. The possibility to refinance old debt causes firm indebtedness to rise, even if profits are decreasing, so this encourages over-leveraging by firms. Financial fragility is expected to increase.

The weak liquidity constraint allows the credit bubble to form until it breaks due to the capital constraint. In this case, there is no bail-out of banks, no recapitalization, so the banks suffer and a credit crunch follows in which banks suddenly refuse to lend. This could lead to many simultaneous illiquidities of firms.

On the other hand, the restrictive liquidity constraint does not allow a credit bubble to form in the first place. It is preemptively cutting the bubble off and forces a deleveraging of debt. There is a higher likelihood of banks staying alive since the lower exposure to fragile firms causes smaller bad debt when they go bankrupt, hence less harm is done to the banking system. Also, the risk of synchronous firm failures is smaller.

A fully accommodating monetary policy by the central bank implies it will step in to provide liquidity to failing banks automatically through the standing facility or discount window. This supports the banks, preventing a bank collapse and they continue to lend to all firms, financially sound or unsound. They also continue to supply new credit to large firms for rolling-over larger debts. The number of supported unsound firms remains high, and bad debt remains high as well. But the collapse in output as seen in the baseline scenario is prevented.

In general, the illiquidities of some healthy firms have been replaced by their insolvencies. This is a good feature, in the sense that the illiquidities signaled an inefficient allocation of credit that resulted in a congestion effect in the credit market. In the scenario with a restrictive reserve requirement, the insolvencies indicate that banks are letting unhealthy firms exit the market instead of supporting them and crowding out the smaller, healthier firms.

Another advantage is that the higher reserve requirement bolsters banks' equity. The relatively high number of bad firms that can be sustained in such a case due to the banks' robustness leads to a *lower* exposure to credit risk. Moreover, this risk exposure is distributed among many banks, reducing the risk that a single bank failure causes a sudden wave of simultaneous firm illiquidities, which would again feedback into the banking system. The banks are robust enough to cope with the negative effects of supporting the financially unsound firms, while at the same time allowing a moderate number of unsound firms to fail. This allows them to support more of the financially healthy firms, and to prevent the congestion effect on the credit market.

5. DISCUSSION

In this paper, we have considered the leverage cycle as the main transmission channel of risk between firms and banks. The traditional transmission channel of monetary policy is through the credit channel, i.e., the broad and narrow channels, that refer to changes in the value of assets on the balance sheets of borrowers and lenders, respectively. This dichotomy, however, overlooks the important role of collateral constraints, which bind the two channels together.

Our analysis shows that a liquidity constraint that prevents banks from fueling a debt bubble, that is mainly caused by the financially unsound firms requiring new debt to roll-over old debt, is of crucial importance for the banks' survival. Hence, such a constraint is highly effective in avoiding deep downturns of the economy.

A CAR is insufficient to ensure the viability of the banks, since without the liquidity constraint the banks might continue to finance certain bad firms and a debt bubble will (re)appear. Sooner or later these bad firms will become insolvent. When this occurs the bad debt will affect the banks' equity, and so reduces the supply of liquidity.

If there is a liquidity constraint in place, the unsound firms are credit constrained first, before they become insolvent, and this causes them to enter into early illiquidity bankruptcy, without the banks' equity being affected too much to cause serious damage to the banking sector. By cutting off the provision of credit to the unsound firms they are also prevented from building up large debts, hence the total bad debt is lower. A debt bubble and subsequent credit crunch does not appear, allowing banks to absorb the moderate write-downs on their balance sheets.

Concerning the effect of different types of credit market regulations on macroeconomic performance, we have four main results wrt. to the amplitude of severe downturns: (i) a more restrictive capital adequacy ratio corresponds to an increase in the amplitude of recessions; (ii) a more restrictive RRR corresponds to a decrease in the amplitude of recessions; (iii) a very tight RRR of 50% or more generically works better to dampen severe downturns than any level of restrictive capital adequacy ratios; and (iv) due to the restrictive liquidity constraint, the illiquidities of healthy firms have been replaced by their insolvency, preventing a congestion effect from occurring on the credit market.

Many avenues for further research on the relationship between firms' financial fragility and banks' systemic risk remain. Next on our research agenda is the analysis of the endogenous dynamics of the firm-bank network of credit relationships. For example, one could study the network of banks just before a crisis occurs, and compare that network structure to the empirical bank network data. We have hinted at this in the main text, where we show that the number of banks that remain active is gradually declining in the system, hence the financial contagion causes a concentration effect in the banking sector. One could also consider the time-evolution of an empirical bank-firm network, with or without considering crisis periods, and then compare the empirical network dynamics to the network dynamics in the model.

TABLE 4. List of parameters

Symbol	Name	Value
Agents		
	Households	1,600
	Consumption goods producers	80
	Investment goods producers	1
	Banks	20
	Central Bank	1
	Government	1
Consumption goods		
γ	Price sensitivity	18
τ	Income tax rate	0.05 (5%)
Credit market		
T	Debt repayment period	18 months
r^{cb}	ECB base interest rate	0.01 (1%)
r^d	Deposit interest rate	0.009 (0.9%)
λ^B	Bank's interest rate multiplier	3
φ	Debt rescaling	0.30 (30%)
Financial market		
α	Capital adequacy requirement	8 (12.5%)
β	Reserve requirement	0.10 (10%)
d	Dividend ratio	0.70 (70%)
n	Months in dividend rule	4

Currently, our model contains only one dynamic network structure that is formed endogenously: the firm-bank network of credit relationships. This could easily be extended to include: (a) an interbank market with bank-to-bank credit relationships; (b) a model with trade-credit with firm-to-firm credit linkages; (c) an extension to explicitly address macroprudential policy issues; (d) stress-testing of individual banks, or of the network as a whole, by tracking the domino-effects of financial contagion, see, e.g., Battiston et al. (2012) for work in this direction.

SUPPLEMENTARY MATERIALS

For supplementary material for this article, please visit https://doi.org/10.1017/S1365100517000219.

NOTES

1. Most Central Banks do not vary the reserve requirement ratio all too often. However, the People's Bank of China (PBOC) uses it as a main policy tool for banking regulation.
2. Models with synchronized decisions, such as production or consumption decisions, might generate unrealistic overshooting effects or give rise to other artefacts such as self-resonant frequencies, see Axtell (2001), Huberman and Glance (1993), Liu et al. (2016). To avoid such issues, the Eurace@Unibi model uses asynchronous timing of individual decision making.

3. The first-come-first-served basis on the credit market refers to the fact that banks provide loans on a daily basis. On a single business day, the bank first collects all credit requests from firms needing credit that day, then sorts these requests based on the firms' default risk. The least risky firm is served first, and so on down the ranking. The next day, a firm that is less risky than the least risky firm of the first day might actually be credit rationed due to the fact that the bank already supplied loans to more risky firms during the first day.

4. The test market consists of a random sample of consumers who are confronted with different sets of products and prices and then report their fictitious purchasing decisions based on the same consumption choice rule they are also employing in their actual consumption decisions.

5. The generic term "investment good" is used to denote machinery and other physical capital goods.

6. All parameter values are listed in Table 4. They result from extensive model calibrations to match empirical stylized facts, as documented in Dawid et al. (2012) and Dawid et al. (2018a).

7. The specification of the probability of default depends on the internal risk model of the banks. The Basel II Accord specifies that banks should use an *objective* ratings-based risk-model, i.e., similar to the models used by ratings agencies, i.e., Moody's, Fitch and Standard & Poor's. Our specification follows Moody's KMV model, which incorporates the Vasicek–Kealhofer (VK) Model [Vasicek (1984), Kealhofer (2003)]. An important assumption in this model is that there exists only one source of market risk, and this is the only risk factor affecting all firms, for example, the aggregate state of the economy. The KMV model is part of the class of structural models, in contrast to the class of reduced models.

8. A similar specification for the interest rate rule can be found in Delli Gatti et al. (2011, p. 67). The difference with our specification is that we use the probability of default, while they use the leverage ratio.

9. An alternative behavioral rule for the bank that we have tested is "partial rationing": When the credit risk exceeds the risk exposure budget V^b, then firm i only receives a proportion of its request, up to the constraint. This rule implies that banks always exhaust their available risk budget and does not result in a viable economy. It leads to more credit rationing rather than less, since firms coming to the bank after a very risky firm has already secured a loan will not be able to receive any loans, because the bank has already exhausted its risk budget.

10. Note that here we use "partial rationing" for the RRR, while for the CAR we use "full rationing."

11. The full robustness analysis is provided in the online appendix.

12. The cumulative loss F^c for a recession with duration k combines the duration and amplitude as a measure for the overall cost of a recession, and is defined as $F^c = \sum_{j=1}^{k}(y_j - y_0) - A^c/2$. Here, y_0 is the level of output at the start of the recession, and y_j are the successive terms during the recession (i.e., the integral under a horizontal line that connects the start of a recession with the end of the recovery). The second term $-A^c/2$ is added in order to penalize a deep short recession more than a shallow long recession, the former being punished more severely due to its higher contribution to macroeconomic costs.

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