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Prudential Regulation in an Artificial Banking System

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Abstract
This study is an exploratory analysis of the economic role of banks under different prudential frameworks. It considers an agent-based computational model populated by consumers, firms, banks, and a central bank whose out-of-equilibrium interactions replicate the conjunct dynamics of a banking system, a financial market and the real economy. A calibrated version of the model is shown to provide an intelligible account of several recurring economic phenomena, thus constituting a favorable ground for policy analysis. The investigation provides a valuable methodological contribution to the field of banking research and sheds new light on the role of banks and their prudential regulation. Specifically, the results suggest that banks are key economic agents. Through their financial intermediation activity, credit institutions facilitate investment and promote growth.

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Keywords Agent-based computational model; financial intermediation; prudential policy; bank regulation

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1 Introduction

Are banks key drivers of economic performance? What are the effects of different macro and micro-prudential regulations on economic growth? These seminal questions have resurfaced in the aftermath of the 2008 financial debacle as a central topic in banking research and as an important source of concern for policy makers. In this study we develop an agent-based computational model through which an exploratory analysis of the economic role of banks under different prudential frameworks is conducted.

The years that preceded the 2008 crisis were characterized by blatantly reckless mortgage lending. Loan-underwriting criteria were so lenient that “subprime” borrowers with no capacity to redeem their debt had easy access to credit. These mortgages were pooled together and used to back collateralized debt obligations (CDOs). As soon as the housing markets collapsed, “domino effects” spread throughout the extremely interconnected financial system, quickly exposing severe fragilities. The price of mortgage-backed securities fell dramatically, and allegedly safe CDOs were, in the end, worthless. The sale of such securities or their use as collateral became increasingly difficult. In an effort to rally liquidity, banks started to sell assets at fire-sale prices, giving rise to “price spiral” phenomena that, in turn, reduced banks’ capital thanks to “mark-to-market” accounting rules. When banks started doubting the solvency of their counterparties, wholesale agents stopped rolling over short-term debt, causing the failure of banks that had relied on non-stable sources of funding (The Economist, 2013).

The financial system proved to be incredibly fragile. Banks had expanded more than ever before, leveraging beyond reasonable levels and holding insufficient capital to absorb losses. It is, therefore, no surprise to note that the ex-post analysis of the failed mechanisms that led to the crisis has focused on banks’ *raison d’être* and on the regulatory instruments that can increase and promote financial stability.

From a theoretical standpoint, banks have long been viewed as fundamental economic agents. Diamond and Dybvig (1983) suggest that banks are useful as liquidity providers since they provide depositors with liquidity insurance against idiosyncratic shocks that affect their consumption needs. In turn, Diamond (1996) suggests that banks provide monitoring services and help decrease asymmetric information between investors and firms. Banks also provide maturity transformation, a process whereby short-term liabilities are converted into long-term assets (Freixas and Rochet, 2008). The literature postulates that agency problems (Dewatripont and Tirole, 1994) and the risk of a systemic crisis (Santos, 2001) are the main reasons why banks should be subject to regulatory requirements.

Across time, several were the instruments - one of the most prominent ones being the deposit insurance scheme proposed by Diamond and Dybvig (1986) – suggested by academia to mitigate or prevent the negative effects of bank bankruptcies. In spite of this, and due to its function in reducing risk-taking and providing a buffer to absorb losses, the regulatory spotlight always fell more brightly upon bank capital (Allen and Gale, 2007). In this regard Basel III/CRD IV rules, which are at present mandatory for Euro area banks, represent the latest regulatory effort to ensure the robustness of the banking system. Besides the enhancement of minimum capital requirements to at least 10.5% of risk-weighted assets, it is worth highlighting Basel III's introduction of a counter-cyclical capital buffer. However, the latest Basel Accord is not completely consensual. Carmassi and Micossi (2012), for instance, argue that Basel III could follow a much simpler path in route to a more stable financial system simply by abandoning the risk weighting approach.

The strong debate surrounding prudential policies, coupled with the blatant failure of macroeconomic models in the 2008 financial crisis, suggests that the study of regulatory policies is not within the grasp of the existing nucleus of mainstream economic knowledge. The notions of interdependence, networks, trust and expectations, which are key to understanding the financial crisis, appear not to be "features of modern macroeconomic models" (Kirman, 2010: 501). To address these shortcomings, it is crucial that economists start considering the economy as a complex evolving system (Taylor, 2007). This can be done through agent-based modeling, a technique that allows researchers to simulate and comprehend out-of-equilibrium economic dynamics (Arthur, 2006).

As illustrated by Tesfatsion (2006), agent-based computational economics encompass a group of technologies that are best used in the analysis of complex, evolving systems composed of a multiplicity of agents who interact on the basis of behavioral rules that are exogenously defined. The incentive for this approach is rooted in the fact that complex systems, of which economies are prime examples, can exhibit emergent phenomena that cannot be foreseen or understood by any agent on an individual level. Instead of modeling economies under the omniscience assumption, according to which the decisions of agents are pre-coordinated, agents are programmed to follow simple behavioral rules that may or may not result in equilibrium. Through computer simulations the behavioral patterns of the system can be scrutinized and understood. Once a computer program able to replicate the phenomena of interest is developed, researchers can use it as a laboratory in which they can conduct policy experiments.

In this vein, it is the purpose of this paper to assess, through the use of a rich, yet tractable agent-based model, the effectiveness and efficiency of prudential regulatory measures in their effort to maintain a stable and sound banking system. We add to the literature by creating a stylized agent-based computational model[1] that simultaneously replicates the conjunct dynamics of a financial market, a banking system and the real economy, mimicking several stylized facts of the latter and grasping, to a certain extent, the implications of banking regulation in economic performance.

The conceptual framework employed draws heavily from Takahashi and Okada (2003) and Tedeschi et al. (2012). For tractability, we adopt a parsimonious approach that drifts away from fully specified models such as the Eurace project (Raberto et al., 2012; Cincotti, 2012). Specifically, our model attempts to depict, in an admittedly stylized form, the inner workings of a small economy comprising consumers, firms, commercial banks and a central bank. Consumers are responsible for providing the work force needed for production and for driving internal demand through consumption. Firms are profit-maximizing entities that produce the consumption good and are thus responsible for driving supply. The primary function of banks is to collect deposits from their clients and to give out loans to consumers and companies. Banks are also subject to prudential rules and regulations established by the Central Bank (i.e., minimum capital ratios and minimum loan underwriting standards).

Following Ashraf et al. (2011), the model is calibrated to U.S. data. Simulations are repeatedly performed, for several time periods and under diverse

[1] The agent-based computational model has been developed in *NetLogo*, a multi-agent programmable modeling environment.

parameter settings to assess how credit institutions affect macroeconomic performance and how performance, in turn, is affected by diverse regulatory frameworks.

With this model model we seek to make a valuable methodological contribution to the field of banking research, shedding new light on the role of banks and bank regulations by leveraging on the advantages of agent-based computational modeling. In spite of being too simple to suit the policy-making endeavor, it does generate five results of broad-spectrum qualitative interest.

The first result corroborates the view that credit institutions are crucial economic agents in so far as their existence greatly improves the performance of the economy. Banks foster growth by providing credit and expanding firms' investment opportunities, which are usually limited to each company's ability to endogenously generate cash flows. The capacity of the economy supply-side to meet aggregate demand is thus substantially improved when a banking system is in place. The role of credit institutions is also relevant in mitigating the negative externalities of firm failures. By providing financing to new entrants and sustaining incumbent firms by preventing capital erosion, banks are often able to alleviate the effects of shocks.

Our second result reveals that the macroeconomic impact of credit institutions and bank regulation often contradicts the traditional dogmas behind micro-prudential policies. In particular, the experiments conducted show that aggregate macroeconomic performance deteriorates as banks become safer (i.e., as stricter capital requirements are imposed). This is because decreased credit availability hampers the creation of value by reducing the speed at which supply can meet surges in demand. Furthermore, increased leverage does not always entail augmented firm bankruptcies. If credit levels are not excessive, bank funding can prevent the depletion of firms' production capacity in periods of low demand, thus contributing to a reduction of bankruptcies in the long run. Finally, increased capital requirements do not always mean that banks are less likely to fail. Indeed, micro-prudential policy is shown to entail calibration risk: while raising capital requirements increases the immediate loss-absorbency capacity of banks, it also decreases their ability to endogenously generate capital through profits.

The third result shows that the role of banks (especially if risky) is more important when the economy is performing well below optimal levels (i.e., when the economy reveals large output gaps). According to our policy experiments the output gap is closed more quickly if banks are allowed to require lower financial autonomy ratios from customers and are subject to lower capital adequacy ratios. In other words, credit is proved to be more important when the output gap is greater.

A corollary of this result is that using the credit-to-GDP ratio as a trigger for the implementation of the counter-cyclical capital buffer might be an insufficient approach if taken alone. Since the same level of leverage may be too high or too low depending on the current state of the economy (i.e., the magnitude of the output gap), the establishment of a counter-cyclical capital buffer must also consider the impact of credit-constraining measures in GDP growth and an assessment of the level of debt that can be sustained by the economy without causing the build-up of system-wide risk.

More importantly, our fourth result argues, under the premises of our model, that the counter-cyclical capital buffer should never actually be implemented. Indeed, our experiments fail to find evidence in support of the rationale behind macro-prudential tools. This conclusion is not surprising if considered together with previous insights, which showed that riskier banks promote growth in fundamentally all scenarios.

Finally, our fifth result suggests that effective resolution is crucial. Specifically, resolution of credit institutions acts to the benefit of the economy by ensuring that depositors are never bailed-in to a great extent and by getting rid of “zombie-banks” that are not able to support investment.

The paper is organized as follows. The next section discusses the conceptual framework of the model and describes the protocol and behavioral rules imposed on its interacting agents. The calibration procedure is also clarified in this chapter. Section 3 describes the core results of our policy experiments, providing insights into the role of banks and the impact of micro and macro prudential policies in economic performance. It also addresses the robustness of the results by examining a scenario in which the negative consequences of bank failures are magnified. Section 4 summarizes our concluding remarks.

2 A stylized model of the banking system

2.1 Conceptual framework

The conceptual framework employed draws heavily upon Takahashi and Okada (2003) and Tedeschi et al. (2012). The model depicts, in an admittedly stylized form, the inner workings of a small economy composed of I consumers, E companies (also referred to as firms), B commercial banks, and a central bank. Consumers are indexed by $i = 1, \dots, I$, companies are indexed by $e = 1, \dots, E$ and banks are indexed by $b = 1, \dots, B$. Since there is no government, there are also no taxes or public expenditure.

In this economy there is only one kind of product valued by the population – the consumption good. Consumer goods are perishable and have their priced fixed at unity.

Two types of production factors exist: labor and capital. Consumers provide labor and receive compensation from companies in return. Based on their disposable income, net worth and bank deposits, consumers determine how much to spend on the consumer good. Companies decide how much to produce based on their production capacity and expectations of demand. During this process firms can invest in infrastructures and technology, increasing their productivity. In general, supply and demand (both internal and external) for the consumer good do not balance, giving rise to demand rationing (excess demand) or production waste.
Economic agents can also invest in financial assets (i.e., bonds), with each debt security generating interest income at each time step. This asset is finite and exogenous to the economy, and can therefore be interpreted as a debt security issued by a sovereign country. Each consumer and company can buy and sell the financial asset in the market.

Bank deposits must mediate all transactions, and proprietors are not able to lend or borrow among themselves. Each bank grants credit and accepts deposits from their customers, with depositors being allocated randomly across banks so that each credit institution starts off with the same number of clients. Transaction settlements are executed by changing the holder of the bank deposit.

For a more comprehensive view of the economy's agents, a cursory description of their core behavioral features and characteristics is provided below.

2.1.1 Consumers

Consumers are responsible for providing the work force needed for production – for which they receive their wage (W) – and for driving internal demand through consumption. They are members of the cooperative firms in which they are employed and are thus entitled to a share of their profits. In addition, consumers are also a large part of the financial asset market since they are able to buy and sell debt securities.

At each time step t, the assets of consumer i are composed of FA_t^i units of the debt security and a bank deposit ($BD_t^{i,b}$). Since companies may not always be able to fulfill their commitments to their employees, circumstances might arise in which the consumer is also owed a part of its salary ($DW_t^{i,e}$). To finance the acquisition of the asset, consumers can make use of bank loans ($BL_t^{i,b}$).

The value of the financial asset is marked to market at each time step:

$$FAV_t^i = P_t FA_t^i \tag{1}$$

Hence, the net worth (i.e., the net equity) of each consumer equals:

$$NW_t^i = FAV_t^i + BD_t^{i,b} + DW_t^i - BL_t^{i,b} \tag{2}$$

The financial autonomy ratio of consumer i can thus be represented as:

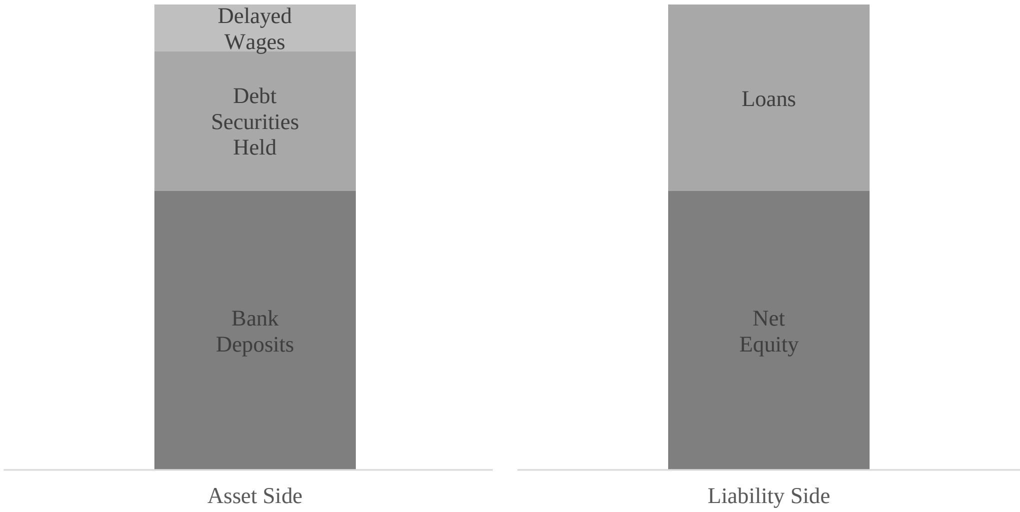
$$ER_t^i = \frac{NW_t^i}{FAV_t^i + BD_t^{i,b} + DW_t^i} \tag{3}$$

Finally, at each time step t, each consumer has a balance-sheet similar to the one depicted in Figure 1.

2.1.2 Companies (also referred to as firms)

Companies are profit-maximizing entities of a cooperative nature (i.e., owned by their employees) that produce the consumption good and are thus responsible for driving supply. The production activity entails the use of two production factors: labor and capital. While the amount of labor is fixed (i.e., each firm has $\frac{I}{E}$ employees), the amount of capital can vary based on investments made by the firm

Figure 1: Consumer's stylized balance sheet



in order to increase its production capacity. Companies are also assumed to be able to invest in the financial asset.

At each time step t, company e owns FA_t^e units of the financial asset, a bank deposit ($BD_t^{e,b}$) and K_t^e of productive capital. In order to finance the acquisition of the asset or increase the production capacity through investment, companies can make use of bank loans ($BL_t^{e,b}$). Finally, and since companies may not always be able to fully remunerate employees for their work, circumstances might arise in which delayed wages are accumulated ($\sum_{i=1}^{\frac{I}{E}} DW_t^{i,e}$, where $DW_t^{i,e}$ represents the amount of delayed wages between company e and consumer i).

Taking into account that the value of the financial asset is marked to market at each time step, the net equity of each firm equals, at time step *t*:

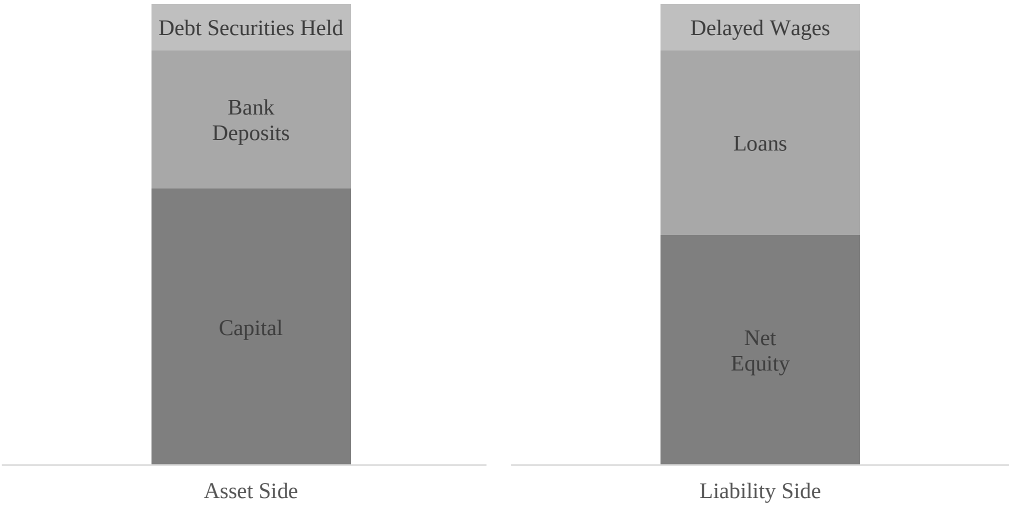
$$NW_t^e = P_t FA_t^e + BD_t^{e,b} + K_t^e - BL_t^{e,b} - \sum_{i=1}^{\frac{I}{E}} DW_t^{i,e} \tag{4}$$

The financial autonomy ratio of company e can be represented as:

$$ER_t^e = \frac{NW_t^e}{P_t FA_t^e + K_t^e + BD_t^{e,b}} \quad (5)$$

Finally, at each time step t, each company has a balance-sheet similar to the one depicted in Figure 2.

Figure 2: Company's stylized balance sheet



2.1.3 Banks

The primary function of banks is to collect deposits from their clients and give out loans to consumers and companies. This financial intermediation activity is undertaken by charging interest on loans and remunerating deposits at a lower rate. Loans are made with full recourse and are collateralized by all the assets of the borrower.

While conducting its operations the bank is subject to mandatory capital requirements and, just like an individual consumer, settles all its transactions through the exchange of deposits.

At each time step t, bank b's assets comprise FA_t^b units of the financial asset, cash holdings (CO_t^b)[2] and loans outstanding ($\sum_{i=1}^{\frac{I}{B}} BL_t^{i,b} + \sum_{e=1}^{\frac{E}{B}} BL_t^{e,b}$). On the other hand, the liability side comprises the shareholders' equity and retail deposits ($\sum_{i=1}^{\frac{I}{B}} BD_t^{i,b} + \sum_{e=1}^{\frac{E}{B}} BD_t^{e,b}$).

Taking into account that the value of the financial asset is marked to market at each time step, the net equity of each bank equals:

$$E_t^b = P_t FA_t^b + CO_t^b + \sum_{i=1}^{\frac{I}{B}} BL_t^{i,b} + \sum_{e=1}^{\frac{E}{B}} BL_t^{e,b} - \sum_{i=1}^{\frac{I}{B}} BD_t^{i,b} - \sum_{e=1}^{\frac{E}{B}} BD_t^{e,b} \quad (6)$$

The capital adequacy ratio of bank b can be represented as:

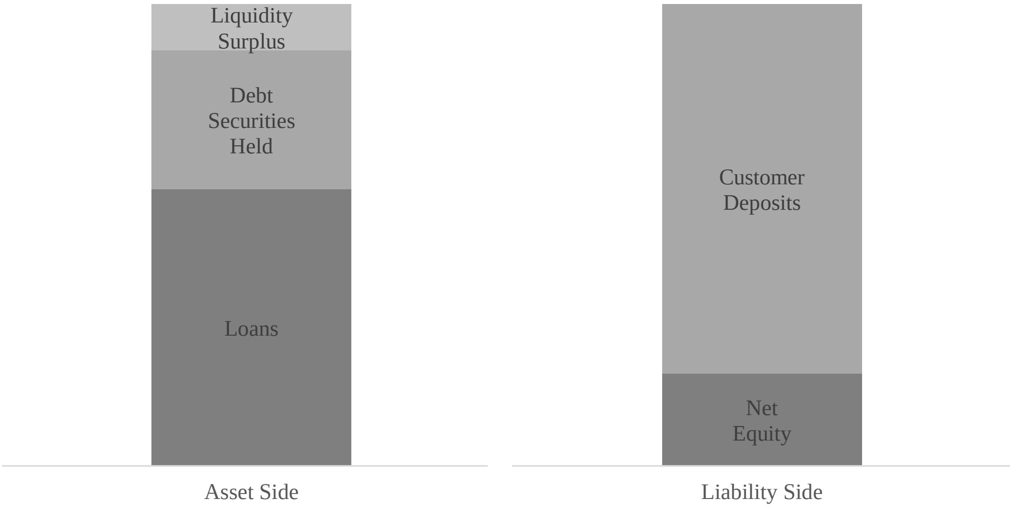
$$ER_t^b = \frac{E_t^b}{RWA_t^b} \quad (7)$$

where the risk-weighted assets (RWA_t^b) represent a risk-based measure of the bank's exposures obtained by multiplying the value of the credit institution's assets by a risk-weight (RW) that varies according to the level of each investment's perceived risk.

The balance-sheet of a bank is depicted in Figure 3.

[2] The cash holdings of the bank include the amount of deposits not currently invested in loans plus the bank's own liquidity surplus. The initial liquidity endowment of banks is denoted by CO_0. Cash holdings are assumed to be applied in foreign (i.e., model exogenous) credit institutions and are thus considered to be interest earning assets.

Figure 3: Bank's stylized balance sheet



2.1.4 Central bank

In the model's economy the central bank is primarily responsible for banking regulation and supervision. The central bank thus regulates banks and is responsible for ensuring their compliance with prudential requirements.

Specifically, the central bank requires each bank to: (i) implement specific loan underwriting policies (as defined by the minimum financial autonomy ratio demanded from customers) and (ii) maintain capital at least equal to a percentage of the value of its risk-weighted assets (bank loans and financial assets). The minimum capital adequacy ratio is represented by ER^b_{min}. Credit institutions that do not comply with this prudential requirement are declared to be in financial distress and are prohibited from granting any new loans. In addition, banks with negative equity are forced into failure by the regulator, giving rise to potential losses for depositors and to the entrance of a new player.

2.2 Protocol and behavioral rules

As usual in the ABM literature, and for the purpose of reducing its computational burden, the model follows a choreographed protocol that restricts the decisions taken by agents and forces them to initiate actions through 11 sequential stages:

1. Determination of internal demand for the consumption good;
2. Determination of external demand for the consumption good;
3. Determination of supply for the consumption good;
4. Loan underwriting;
5. Assessment of companies' financial position;
6. Companies' bankruptcy and entrance;
7. Assessment of consumers' financial position;
8. Assessment of banks' financial position;
9. Banks' bankruptcy and entrance;
10. Purchase and sale of the financial asset;
11. Distribution of profits.

Each of these steps is described in detail below.

1. Determination of internal demand for the consumption good

The level of consumption is assumed to be determined as a function of the consumer's disposable income and net worth at the beginning of the period:

$$C_t^i = min\left(\left(\alpha Y_{t-1}^i + \beta NW_{t-1}^i\right) \times (1+\theta); BD_{t-1}^{i,b}\right) \quad (8)$$
$$\theta \sim N(0,\sigma)$$

where α represents the marginal propensity to consume from income, β represents the marginal propensity to consume out of net wealth, and θ is a normally distributed random variable that accounts for all other motives that may increase or decrease consumption. It should be noted that consumption is always limited by the amount of cash (i.e., bank deposits) the consumer owns at the beginning of the period.

2. Determination of external demand for the consumption good

Since the model focuses on an open economy, demand for the consumer good is not only internal. External demand (e.g., exports), which is firm specific, is defined exogenously and assumed to grow at a rate of g_0:

$$X_t^e = X_{t-1}^e \times (1 + g_0 + \theta) \quad \theta \sim N(0, \sigma) \tag{9}$$

where θ is a normally distributed random variable that accounts for the myriad of factors that may affect exports at each moment in time.

3. Determination of supply for the consumption good

Companies plan their production activity based on the observed last period's demand. Demand is assumed by firms to increase at a constant rate, thus mimicking long term expectations of economic growth. Since producers are undifferentiated, expected internal demand is equally distributed across firms:

$$E[D]_t^e = \left(\frac{\sum_{i=1}^{I} C_{t-1}^i}{E} + X_{t-1}^e\right) \times (1 + g_0) \tag{10}$$

To produce the consumer good, companies use capital as the only input. Each firm can produce according to the following production function:

$$S_t^e = \phi K_t^e \tag{11}$$

For simplicity purposes, capital productivity ϕ is assumed to be constant and uniform across companies. In addition, capital is assumed to depreciate at a constant rate (ϖ) at each time step.

Companies will initially try to produce as much as their expected demand. Since the only external source of finance that firms have are bank loans, firms will apply for credit whenever their capital is not enough to meet expected demand.

However, since borrowing entails the risk of default, each company takes into account its probability of failure when submitting a loan application.[3] Credit demanded by company e to bank b is thus established according to:

[3] Companies are assumed to be rational, which means that they will apply for a loan only if they expect to have profits in the future. When this condition is satisfied, firms may seek external funding. In particular, they will require bank financing if the amount of capital they own is less than the amount of capital required to meet expected demand. The second term of Equation (12) establishes the amount of credit that the company would request from the bank if it did not take into account any risk considerations. However, since borrowing entails the risk of default, each company considers its probability of failure when submitting a loan application. It does this by comparing expected profits with expected debt servicing costs. If the firm expects future profits not to be enough to pay back its installments, it will ask for a reduced loan amount. The higher the risk aversion coefficient, the more

$$BL_{*}^{e,b} = \begin{cases} \varphi\left(1 - \frac{\overline{BL_{t+1}^{e}}}{E[\pi_{t+1}]}\right) \times \max\left(\frac{E[D]_t^e}{\phi} - S_t^e, 0\right) & for\ E[\pi_{t+1}] > 1 \\ 0 & otherwise \end{cases} \quad (12)$$

where φ is the firm's risk aversion coefficient, $E[\pi_{t+1}]$ represents the firm's expected profits and $\overline{BL_{t+1}^{e}}$ represents the firm's expected debt servicing costs.

4. Loan underwriting

Credit granting is determined as a function of the financial situation of the borrower and the capital position of the bank. In an effort to replicate the "restricted lending" problems typical of the recent financial crisis, credit institutions with adequate capital are assumed to be more willing to take risks, whereas banks with inadequate capital become reluctant to lend funds. The level of loan affordability depends on the capital ratio of the bank and takes on the value zero if its capital ratio (ER_t^b) stays below ER_{min}^b or the capital ratio of the borrower (ER_t) is below ER_{min}. Naturally, the bank must also have liquidity surpluses (i.e., cash holdings) to underwrite the loan. The amount of credit to be granted by the bank[4] is thus defined as follows:

$$BL_t^b = \begin{cases} 0 & for\ ER_t^b < ER_{min}^b \vee ER_t^i < ER_{min}^i \vee CO_t^b \leq 0 \\ \min\left(BL_*^b, \frac{(ER_t^b - ER_{min}^b) \times RWA_t^b}{RW}, CO_t^b\right) & for\ (ER_t^b - ER_{min}^b) \times RWA_t^b < BL_*^i \times RW \quad \times ER_{min}^b \wedge ER_t^i > ER_{min}^i \\ \min(BL_*^i, CO_t^b) & for\ (ER_t^b - ER_{min}^b) \times RWA_t^b > BL_*^i \times RW \quad \times ER_{min}^b \wedge ER_t^i > ER_{min}^i \end{cases} \quad (13)$$

Interest rates are assumed to be determined exogenously as a result of competition, changing as a result of the excess demand or supply of funds in the financial market. In particular, the interest rate on deposits negatively depends on the amount of deposits held by banks:

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the loan application amount is reduced. This "financial fragility" aspect is reflected in the first term of Equation (12).

4 More concretely, the bank grants no credit whenever: (i) its capital ratio stays below the regulatory minimum, (ii) the capital ratio of the borrower is below the required minimum or (iii) the bank has no liquidity surpluses to underwrite the loan. If the three abovementioned premises are fulfilled, the bank may grant the loan. However, the amount granted is limited by the bank's (i) cash holdings and (ii) capital buffer. Indeed, it may be the case that the total amount of financing required by the company is superior to the banks liquidity surplus or ability to leverage. In such cases, the amount granted must be rationed. On the contrary (i.e., if the three abovementioned premises are fulfilled and the bank's capital buffer is above the loan's capital consumption), the bank grants the minimum between the requested amount and its liquidity surplus.

$$r^d = \frac{2 \times \bar{r}}{1 + \exp\left(\frac{\sum_{i=1}^{I} BD^i + \sum_{e=1}^{E} BD^e - \sum_{i=1}^{I} BL^i - \sum_{e=1}^{E} BL^e}{I \times \bar{C}}\right)} \tag{14}$$

where $\bar{r}$ represents the average interest rate on deposits and $\bar{C}$ the average level of consumption.

Since loans to domestic investors involve the risk of bankruptcy, banks charge higher interest rates on loans. The rate is bank-idiosyncratic and inversely correlated to the financial robustness of the institution:

$$r_t^{l,b} = r^d + \lambda \times \left(\frac{\sum_{i=1}^{I} BL^{i,b} + \sum_{e=1}^{E} BL^{e,b}}{CO_t^b}\right) \tag{15}$$

where λ is a representative parameter of the bank's risk aversion.

All loans are based on variable interest rates, which means that the interest rate charged on the outstanding balance varies as market interest rates change. In addition, all loans are initially given out with a standard maturity M. When a consumer or a company increases the amount of borrowings received from the bank, the total amount of debt commitments is, in a process akin to debt restructurings, merged into a single loan that will mature within M timesteps.

Loans are considered to be in distress when at least one payment has been missed. Each bank determines a liquidation rule such that each of their customers goes bankrupt whenever they miss BPM^i consecutive payments.

5. *Assessment of companies' financial position*

After trying to sell their production in the market, companies assess their cash in-flows and start making their payments. At this point, each firm's revenues[5] are given by the remuneration generated by each unit of bonds owned and the minimum between real demand and the company's production:

5 Firm's revenues also include interest received on deposits and potential cash-inflows stemming from the sale of debt securities. At this point, however, it is not possible to know whether the revenue generating capacity of the company's bank is enough to meet the totality of its commitments. Interest revenue is thus added to the firm's net worth after the computation of the bank's financial position (refer to Stage 8). In addition, proceeds from the sale of debt securities are added to the firm's bank deposits whenever a transaction is settled (refer to Stage 10).

$$Cash\ inflow_t^e = \min\left(\frac{\sum_{i=1}^{I} C_{t-1}^i}{E} + X_{t-1}^e;\ S_t^e\right) + r^f \times FA_t^e \times FANV \tag{16}$$

where r^f is the coupon rate of the debt security and $FANV$ represents its nominal value.

On the other hand, cash outflows[6] are given by:

$$Cash\ outflow_t^e = \left(\frac{I}{E+B} \times W\right) + r^{l,b} \times BL_t^{e,b} + \frac{BL_t^e}{M} \tag{17}$$

where $\left(\frac{I}{E+B} \times W\right)$ represents personnel costs, $r^l \times BL^i$ represents funding costs and $\frac{BL_t^e}{M}$ represents the loan's principal repayment.

Whenever cash outflows are greater than cash inflows plus the company's deposits, the firm gives priority to the payment of wages. Bank loans are assumed to be paid last. Amounts not paid are registered as liabilities and need to be paid in the following time step. In an effort to re-balance its financial position, the company will also try to sell any bond it owns.

Finally, the company net worth is updated as follows:

$$NW_t^e = NW_{t-1}^e + Cash\ inflow_t^e - Cash\ outflow_t^e \tag{18}$$

6. Companies' bankruptcy and entrance

As already stated, banks will liquidate debtors as soon as they miss BPM^i payments. In such situations, the remaining company's assets are seized by the bank and the player leaves the market.

The model assumes a simple entry mechanism based on one-to-one replacement. As such, firms that go bankrupt are automatically replaced by new players. From the empirical literature (Bartelsman and Scarpetta, 2005), new entrants are usually smaller than existing firms. Specifically, the stock of capital of

[6] Firm's cash-outflows also include potential payments stemming from the purchase of debt securities and from the distribution of dividends. Disbursements associated with the acquisition of financial assets are deducted from the firm's bank deposits whenever a transaction is settled (refer to Stage 10). Cash-outflows associated with dividend payouts are deducted from the firm's net worth at the end of each time step (refer to Stage 11).

new firms is drawn from a uniform distribution with $a = \min(K_t^1, K_t^2, \dots, K_t^E)$ and $b = \text{median }(K_t^1, K_t^2, \dots, K_t^E)$.

7. Assessment of consumers' financial position

At this stage, the income of consumer i in period t (Y_t^i)[7] is a function of its wage and the amount of bonds it owns. This can be represented as:

$$Y_t^i = W + r^f \times FA_t^i \times FANV \tag{19}$$

Note that the consumer might not always receive the totality of its wage, as the company for which it works might be in financial distress.

On the other hand, the cash outflow[8] of each consumer at time step t is given by:

$$Cash\ outflow_t^i = C_t^i + r^{l,b} \times BL_t^{i,b} \tag{20}$$

where C_t^i represents consumption and $r^{l,b} \times BL^{i,b}$ represents funding costs.

Whenever cash outflows are greater than income plus the consumer's deposits, the consumer gives priority to the liquidation of consumption expenses. Bank loans are assumed to be paid last. Amounts not paid are registered as liabilities and need to be paid in the following time step. In an effort to re-balance its financial position, the consumer will also try to sell any bond it owns.

Finally, the consumer's net worth is updated as follows:

$$NW_t^i = NW_{t-1}^i + Y_t^i - Cash\ outflow_t^i \tag{21}$$

[7] Consumer's income also includes interest received on deposits and potential cash-inflows stemming from the sale of debt securities and from firm dividends. At this point, however, it is not possible to know whether the revenue generating capacity of the consumer's bank is enough to meet the totality of its commitments. Interest revenue is thus added to the consumer's net worth after the computation of the bank's financial position (refer to Stage 8). In addition, proceeds from the sale of debt securities are added to the consumer's bank deposits whenever a transaction is settled (refer to Stage 10). Cash inflows associated with firm dividends are added to the consumer's net worth at the end of each time step (refer to Stage 11).

[8] Consumer's cash-outflows also include potential payments stemming from the purchase of debt securities. Such disbursements are deducted from the consumer's bank deposits whenever a transaction is settled (refer to Stage 10).

8. Assessment of banks' financial position

At each time step banks will assess their cash-flows to determine the robustness of their financial position. Cash inflows[9] consist fundamentally of interest income and are thus a function of the debtors' ability to service their debt and the rate of remuneration of the bank's claims on other (foreign) credit institutions:

$$Cash\ inflow_t^b = \sum_{i=1}^{\frac{I}{B}} \left(r^{l,b} \times BL_t^{b,i}\right) + \sum_{e=1}^{\frac{E}{B}} \left(r^{l,b} \times BL_t^{b,e}\right) + r^{ci} \times CO_t^b \tag{22}$$

In accordance with commercial banks' business models, cash outflows[10] consist of interest expenses related to the remuneration of deposits:

$$Cash\ outflow_t^b = \sum_{i=1}^{\frac{I}{B}} \left(r^d \times BD_t^{b,i}\right) + \sum_{i=1}^{\frac{E}{B}} \left(r^d \times BD_t^{b,e}\right) \tag{23}$$

Liquidating distressed borrowers is needed for banks to raise liquidity, thus playing a crucial role in banks' financial stability. As already stated, banks will liquidate debtors (consumers or companies) as soon as they miss BPM^i payments. In this process credit institutions take over any bond still owned by the debtor[11] and immediately try to sell it on the market. The transfer of the collateral's ownership implies a direct write off of the bad loan.

Whenever cash inflows are greater than cash outflows plus the bank's cash holdings, it is clear that the credit institution is able to meet the totality of its commitments. The net worth of both companies and consumers is thus increased by their respective remuneration on deposits:

$$NW_t^i = NW_t^i + r^d \times BD_t^{i,b} \tag{24}$$

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[9] Banks' cash-inflows also include potential revenues stemming from the sale of debt securities. Such proceeds are added to the banks' deposits whenever a transaction is settled (refer to 10).

[10] Banks' cash-outflows also include potential payments stemming from the purchase stage of debt securities. Such disbursements are deducted from the banks' bank deposits whenever a transaction is settled (refer to 10).

[11] Note that the stage debtor will not have any asset at this point, since all deposits/cash have already been used to try to pay off its debts.

$$NW_t^e = NW_t^e + r^d \times BD_t^{e,b} \tag{25}$$

Finally, the bank net worth is updated as follows:

$$NW_t^b = NW_{t-1}^b + Cash\ inflow_t^b - \ Cash\ outflow_t^b - NPL_t^b + P_t \times FFA_t^b \tag{26}$$

where NPL_t^b stands for the non-performing loans that were written off by bank b in time step t and FFA_t^b represents the number of debt securities foreclosed during the same time step.

9. Banks' bankruptcy and entrance

Bankruptcy is assumed to happen to banks whenever credit institutions are not able to fulfill the totality of their commitments (i.e., whenever cash outflows are greater than cash inflows plus the bank's cash holdings) or whenever their capital ratio is below zero. The model thus captures the possibility for both liquidity and solvency related default events.

In the event of bankruptcy, the credit institution enters into resolution. As part of this process, non-performing loans (i.e., loans with $BPM_t^i > 0$) are foreclosed. Debtors that were not able to fully pay their obligations to the bank see their holdings confiscated. Since the collateral's value may not be enough to fully compensate non-performing loans outstanding, the bank's capital might be further reduced during this process.

After all the non-performing loans are foreclosed, the capital position of the bank is assessed. Losses are first absorbed by equity capital. Depositors are bailed-in whenever equity capital is negative. Since all depositors have the same level of seniority, losses are distributed among all clients proportionally to the amount of deposits they own.

Similarly to the process described in Point 6, a recapitalization of the bank using foreign capital is assumed. Since only healthy assets are now left in the bank, this does not constitute a farfetched scenario. The amount of the recapitalization is equal to the maximum between the endowment initially given to all banks and the amount of capital needed for the bank to obtain a capital adequacy ratio 12% in excess of minimum requirements. When computing the latter, a haircut (h) is applied to the value of the financial assets.

10. Purchase and sale of the financial asset

Supply and demand for the financial asset are generally determined by how attractive the bond is vis-à-vis other financial assets (loans). For each agent, the attractiveness of the debt security in period t, denoted by x_t, is given by:

$$x_t = y_t + (2\delta_1\tilde{\gamma} - \delta) - r_t^l \tag{27}$$

where

$$y_t = \frac{FANV \ \times r^f + \ \delta_2\tilde{\gamma}(P_{t-t_\zeta} - P_{t-1})}{P_{t-1}} \tag{28}$$

and

$$\tilde{\gamma} \sim U \ between \ 0 \ and \ 1 \tag{29}$$

The first term on the right-hand side of Equation (28) represents the expected income accrued from owning one unit of the financial asset. The second term captures the expected capital gain perceived by the trend chasers augmented by δ_2, the strength of the trend-chasing attribute. Expected capital gains in Equation (28) reflect the change in the asset price over the last $t - t_\zeta$ periods. Even though all traders are trend chasers, the capital gain term is weighted by a random variable ($\tilde{\gamma}$) to capture divergent expectations.

The gains from holding debt securities (first term of Equation (27)), minus loan interest (denoted by the third term), measure the marginal net gain from owning an additional bond. In reality, other factors affect purchase and sale decisions: the second term of Equation (27) represents such factors. This second term further helps traders to form different expectations.

The owner attempts to sell one bond when it judges bonds to be less attractive (i.e., less than $\bar{x}$), or when it is pressed to sell due to a financial distress situation. For $FA_t \geq 1$, supply of bonds (FAS_t) is such that:

$$FAS_t = \begin{cases} 1 & if \ x_t < \bar{x} \lor BPM_t > 0 \lor ER_t < 0 \\ 0 & otherwise \end{cases} \tag{30}$$

Unless they are debtors of non-performing loans, economic agents will try to purchase one unit of the financial asset if having the additional unit is attractive enough:

$$FAD_t = \begin{cases} 1 & if\ x_t > \bar{x} \\ 0 & otherwise \end{cases} \quad (31)$$

After defining its interest in buying the financial asset, every agent needs to determine if it needs bank financing. Buy-side players' intention to acquire debt securities is limited to the purchase of one unit.

After each agent determines its market positioning, supply and demand meet randomly, resulting in transactions. The short side of supply or demand determines the actual quantity of units traded. Agents that manage to settle their transactions see their financial position updated accordingly:

$$NW_t = NW_t - P_t \times BP_t + P_t \times BS_t \quad (32)$$

where BP_t represents the amount of debt securities purchased and BS_t represents the amount of debt securities sold.

In general, prices are assumed to be sticky. The price, therefore, responds to the difference between supply and demand (G_t), with ψ representing the speed of the price adjustment:

$$P_t = \psi G_t + P_{t-1} \quad (33)$$

where

$$G_t = P_{t-1} \times \frac{\sum FAD_t - \sum FAS_t}{\max(\sum FAD_t, \sum FAS_t)} \quad (34)$$

11. Distribution of profits

At the end of each time step, in accordance with their cooperative nature, firms distribute dividends. The payout ratio is a function of both the firm's current cash holdings and the outflows that the company expects to face in the next period. Specifically, expected disbursements reflect each firm's forecasted personnel and investment costs. Mathematically:

$$Dividend_t^e = \max\left(DP_t^{e,b} - K_t^e \times \varpi - \left(\frac{I}{E+B} \times W\right) - \frac{E[D]_{t+1}^e - S_{t+1}^e}{\phi} \times \varrho, 0\right) \quad (35)$$

where $E[D]_{t+1}^e$ represents the next period's expected demand, S_{t+1}^e represents the next period's production capacity and ϱ designates each firm's propensity to fund new investments with equity (i.e., the percentage of cash withheld to fund new investment opportunities or, in other words, the target capital structure of greenfield projects).

Naturally, and in case the distribution of profits is compatible with the liquidity position of each company, the net worth of each of its associates must be updated with their respective share of the dividend:

$$NW_t^i = NW_t^i + \frac{Dividend_t^e}{\frac{I}{E+B}} \tag{36}$$

Finally, each company's net worth is updated as follows:

$$NW_t^e = NW_t^e - Dividend_t^e \tag{37}$$

2.3 Model calibration

As demonstrated above, the model has multiple individual agents. In order to restrain the number of parameters and to facilitate calibration, ex-ante symmetry between agents was imposed. In spite of the homogenous initial setting, the economy develops heterogeneous behaviors and results due to the impact of feedback effects and noise.

The calibration procedure follows the methodology described in Ashraf et al. (2011) and assumes that each time step represents one month. The 39 parameters of the model were classified as consumer parameters, firm parameters, bank parameters, financial market parameters, and general parameters. These are listed in Table 1 along with the assigned values under the baseline scenario. A comprehensive list of the model's variables is also provided in Table 2.

The calibration of these parameters encompassed three different stages. During the first stage one subgroup of parameter values was chosen based on empirical U.S. data or the values used in earlier studies. The extensive simulations performed identified specific parameters that tended to converge, on average across simulations, to a specific value. The identification of these parameters comprised the second stage of the calibration process. Finally, during the third stage the values of the outstanding parameters, for which no suitable empirical evidence was found, were chosen in order to (i) guarantee that the model replicates

Table 1: Calibrated model parameters

	Consumer parameters	
I	Number of consumers in the economy	1,000
α	Propensity to consume out of disposable income	0.95
β	Propensity to consume out of net wealth	0.01
σ	Volatility of the shock to consumption	0.1
W	Wage	500
BD_0^i	Initial liquidity endowment provided to consumers	5,000
FA_0^i	Initial amount of debt securities held by each consumer	1
	Firm parameters	
E	Number of firms in the economy	50
K_0^e	Initial capital endowment provided to firms	150,000
ϕ	Capital productivity	0.1
ϖ	Capital depreciation rate	0.6%
BD_0^e	Initial liquidity endowment provided to firms	150,000
φ	Firm's risk aversion coefficient when submitting its loan application	1
FA_0^e	Initial amount of debt securities held by each firm	1
ϱ	Firm's propensity to fund new investments with equity	45%
	Bank parameters	
B	Number of banks in the economy	10
CO_0	Initial liquidity endowment provided to banks	250,000
λ	Bank's risk aversion coefficient when defining the spread on loans	0.1
r_0^d	Initial interest rate on deposits	0.17%
r^{ci}	Interest rate received due to claims on foreign credit institutions	0.15%
BPM^i	Number of missed payments necessary for liquidation to be triggered	3
M	Standard maturity of loans granted	12
ER_{min}^b	Minimum bank capital adequacy ratio	8%
ER_{min}^e	Minimum financial autonomy required of firms to be eligible for loans	70%
ER_{min}^i	Minimum financial autonomy required of consumers to be eligible for loans	70%
RW_{ci}	Risk-weight on loans to foreign credit institutions	20%
RW	Risk-weight on risky assets	62.5%
h	Haircut applied to the value of the financial asset when estimating recapitalization needs	50%
FA_0^b	Initial amount of debt securities held by each bank	0

	Financial market parameters	
r^f	Coupon rate of the debt security	0.17%
$FANV$	Notional amount of the debt security	300,000
P_0	Initial price of the financial asset	2055
δ	Agents' propensity to form divergent expectations regarding the financial asset price	0.5
δ_1	Agents' propensity to form divergent expectations regarding the financial asset price	0.2
δ_2	Strength of the trend-chasing attribute	1
$\bar{x}$	Attractiveness threshold for the financial asset	0.01
ψ	Price adjustment speed	0.1
	General parameters	
g_0	Expected growth of internal and external demand	0.26%
X_0	Initial amount of external demand	56,000

Table 2: Model variables

	Consumer variables
$DW_t^{i,e}$	Wages in arrears
FA_t^i	Debt securities held
$BL_t^{i,b}$	Outstanding bank loans
$BD_t^{i,b}$	Bank deposits owned
FAV_t^i	Mark-to-market value of the financial assets held
NW_t^i	Consumer's net worth
ER_t^i	Financial autonomy ratio
C_t^i	Level of consumption
Y_t^i	Disposable income
$\bar{C}$	Average level of consumption
	Firm variables
FA_t^e	Debt securities held
$BD_t^{e,b}$	Bank deposits owned
K_t^e	Productive capital
$BL_t^{e,b}$	Outstanding bank loans

NW_t^e	Firm's net worth
ER_t^e	Financial autonomy ratio
X_t^e	External demand
$E[D]_t^e$	Expected internal demand
S_t^e	Firm's production
$\overline{BL_{t+1}^e}$	Expected debt servicing costs
$E[\pi_{t+1}]$	Expected profits
	Bank variables
FA_t^b	Debt securities held
CO_t^b	Cash holdings
E_t^b	Net equity
ER_t^b	Financial autonomy ratio
RWA_t^b	Risk-weighted assets
BL_*^b	Loan amount required by the applicant
r^d	Interest rate on deposits
$\bar{r}$	Average interest rate on deposits
$r_t^{l,b}$	Interest rate on loans
FFA_t^b	Foreclosed financial assets
NPL_t^b	Written-off non-performing loans
	Financial market variables
P_t	Price of the financial asset
FAS_t	Supply for the financial asset
FAD_t	Demand for the financial asset
BP_t	Bonds purchased
BS_t	Bonds sold
G_t	Difference between supply and demand

some of the most well known stylized facts of real economies and (ii) make the model's median outcome across simulations of specific outputs (e.g., GDP) loosely match the properties of U.S. data.

2.3.1 First stage of the calibration

Consumer parameters. Following Takahashi and Okada (2003):

- The consumer's propensity to consume out of disposable income (α) was set to 0.95;
- The consumer's propensity to consume out of net wealth (β) was set to 0.01;
- The initial wage of each worker (W_0) was set to 500.

Analogously to the volatility of the shock to aggregate demand defined by Tedeschi et al. (2012), the volatility of the shock to each agent's consumption (σ) was set to 0.1.

Firm parameters. In accordance with Tedeschi et al. (2012):

- Capital productivity (ϕ) was set to 0.1;
- Each firm's risk aversion coefficient when submitting loan applications (φ) was set to 1.

Bank parameters. As defined by Tedeschi et al. (2012):

- Each bank's risk aversion coefficient used to define the spread on granted loans (λ) was set to 1;
- The standard maturity of every loan (M) was set to 12 (i.e., 1 year).

As foreseen in the Basel III capital accord, the minimum capital adequacy ratio (ER^b_{min}) was set at 8% (capital buffers not included). The risk-weight (RW) on non-risk-free assets is approximated by the average Basel II RWA density[12] reported by Le Leslé and Avramova (2012). The risk-weight attributable to claims on other credit institutions (RW_{ci}) is set at 20%, which is the weight foreseen in CRD IV/CRR for claims on banks belonging to the best credit quality step.

Finally, and based on Banco de Portugal's definition of credit-at-risk,[13] the number of missed payments necessary for the bank to trigger the liquidation of a debtor was set at 3 (i.e., 90 days).

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12 Percentage of RWAs over total assets.

13 The concept of credit-at-risk was initially defined by Banco de Portugal in Instruction No 22/2011. Credit-at-risk corresponds to the following elements as a whole: (a) Total amount of outstanding loans with principal installments or interest overdue for a period of 90 days and over.

Financial market parameters. Following Takahashi and Okada (2003):

- Each agents' propensity to form divergent expectations regarding the financial asset price (as measured by δ and δ_1) were set to 0.5 and 0.2, respectively;
- The strength of the trend-chasing (δ_2) was set to 1;
- The attractiveness threshold for the financial asset ($\bar{x}$) was set to 0.01;
- The price adjustment speed (ψ) was set to 0.1.

General parameters. The long-term growth expectation of internal and external demand (g_0) was set at 0.26% based on the monthly growth rate of the US economy between 1947 and 2014 according to the data series available at the Federal Reserve Bank of St. Louis. To estimate the growth rate, and taking into account that our model does not consider inflation (i.e., the price of the consumer good is fixed at unity), the data series for the real gross domestic product[14] was used.

2.3.2 Second stage of the calibration

During the calibration phase of the model the price of the debt security (P_t) was found to show mean reverting behavior. As such, its initial value was set to 2055 (i.e., the median value of the cross-run averages of the security's price).

2.3.3 Third stage of the calibration

After the first and second stages, 20 parameters still required calibration. To define them, the behavior space of the model was analyzed in detail. The model was run

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Non-contracted current account claims should be considered as credit-at-risk 90 days after an overdraft is recorded; (b) Total amount of outstanding restructured loans not covered by the preceding sub-paragraph, whose installment or interest payments, overdue for a period of 90 days and over, have been capitalized, refinanced, or their payment date delayed, without an adequate reinforcement of collateral (this should be sufficient to cover the total amount of outstanding principal and interest) or the interest and other overdue expenses that have been fully paid by the debtor; (c) Total amount of credit with principal installments or interest overdue for at least 90 days, but on which there is evidence to warrant classification as credit-at-risk, notably a debtor's bankruptcy or winding-up.

[14] Inflation adjusted (billions of chained 2009 dollars), seasonally adjusted, quarterly value of the goods and services produced by labor and property located in the United States.

several times while systematically varying its settings and recording the results of each run. This "parameter sweeping" process allowed us to explore the model's potential behaviors and identify which combinations of settings caused the phenomena of interest. Behaviors of interest were identified whenever the model was able to (i) replicate some of the most well-known stylized facts of real economies and (ii) make the median outcome across simulations of specific outputs (e.g., GDP) loosely match the properties of U.S. indicator variables.

In particular, 1000 simulations of 40 years (i.e., 480 time steps) were performed. For each run the average of each indicator variable was computed using only the last 35 years to eliminate transients and capture only the system's stochastic steady state. Finally, the median of the simulation averages was computed. The only exception to this methodology was the calculation of GDP related variables, which were assessed based on a time series composed of the cross-run average of the economy's domestic product at each time step.

With regard to the real values of U.S. data used, it is important to note that:

- GDP's volatility is the standard deviation of the detrended HP-filtered log GDP series for the period 1947-2014. As suggested by Ravn and Uhlig (2002) for quarterly data, the value of the multiplier parameter was set at 1600. The autocorrelation of this variable was computed by estimating an AR(1) process over the same time period.
- The default rate is the value-weighted average of rated corporate bond issuers that entered into financial distress each year between 1920 and 2010, which Moody's (2011) reports to be 1.15 percent. At this juncture it is important to acknowledge that circumscribing the data to the exit rate on rated corporate bond issuers is most likely severely underestimating the aggregate default rate of regular companies in the U.S.
- Finally, and according to Ashraf et al. (2011), the average yearly commercial bank bankruptcy rate stood at approximately 0.51 percent over the period from 1984 to 2006.

The real U.S. variable values are enumerated in Table 3 together with the median output of the calibrated model. As the figures show, the model is modestly effective in mirroring real data. Specifically, the model underestimates the average growth of the economy and GDP volatility, while overestimating GDP's autocorrelation and the U.S. economy's default rates for firms and banks.

In addition, the model is also successful in replicating several of the stylized facts thoroughly surveyed by King and Rebelo (1999) with respect to the U.S. real aggregate activity. To study these properties and assess their emergence in the model, we focus on a time series composed of the cross-run average of each variable at each time step.

Non-stationarity. From Figure 4 it is clear that the log GDP fluctuates around a long-run growth trend. The non-stationarity of the series is also corroborated by the Augmented Dickey-Fuller ("ADF") test (refer to Table A1 in the Appendix), according to which the null hypothesis cannot be rejected (p-value of 96.29 %).[15]

Persistence. All detrended business cycle variables (refer to Table 4) show substantial persistence (average first order autocorrelation of 0.68), which means that shocks have a real effect on the evolution of each economic cycle.

Table 3: U.S. data vs. Model's median outcomes

	Data	**Model**
GDP growth	3.19%	3.69%
GDP volatility	3.29%	0.86%
GDP autocorrelation coefficient	0.85	0.93
Firms' default rate	1.15%	1.49%
Banks' default rate	0.51%	0.57%

15 Based on the ADF test it is also possible to conclude that the series follows a deterministic trend (i.e., it is trend stationary). This conclusion is based on the fact that the null hypothesis is rejected (p-value of 0%) when conducting the ADF test with trend and intercept (refer to Table A2 in the Appendix). However, this specific characteristic is a byproduct of the cross-run averaging process in which the impact of the stochastic shocks is smoothed. This is corroborated by the analysis of an example test run (seed –397426811), which follows a stochastic trend according to the ADF test (p-value of 82.4%; refer to Table A3 in the Appendix).

Figure 4: Cross-run average of the log GDP in the model's baseline calibration

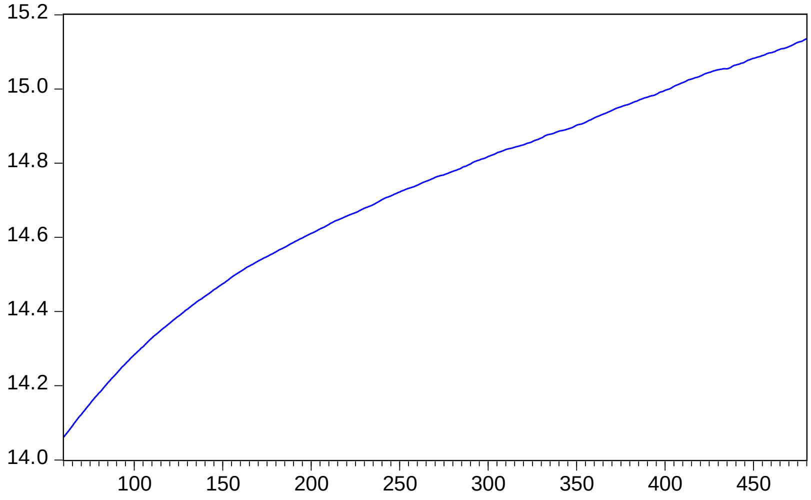


Table 4: Business cycle statistics in the model's economy

	Annualized standard deviation	Relative standard deviation	First-order autocorrelation	Contemporaneous correlation with output
Model				
GDP	0.86%	1.00	0.93	1.00
Consumption	0.55%	0.65	0.77	0.65
Investment	3.74%	4.35	0.11	0.33
Real U.S. data				
GDP	3.29%	1.00	0.85	1.00
Consumption	1.35%	0.74	0.80	0.88
Investment	5.30%	2.93	0.87	0.80

All model values are in logarithms and have been detrended using the HP filter. As suggested by Ravn and Uhlig (2002) for monthly data, the value of the multiplier parameter was set at 129600.

Source: Consumption and investment statistics for the U.S. economy retrieved from King and Rebelo (1999)

Volatility. The detrended macroeconomic aggregates produced by the model also replicate real phenomena concerning levels of dispersion:

- Consumption is less volatile than output (relative standard deviation of 0.65);
- Investment is much more volatile than output (relative standard deviation of 4.35);

Comovement. Most of the economic variables are pro-cyclical, thus exhibiting a positive contemporaneous correlation with the output (average correlation coefficient with the output of 0.74).

Finally, it is also worth highlighting that the model is able to mimic relevant relationships among macroeconomic variables that hold over long horizons. In analyzing the model's capacity to replicate stylized facts of economic growth and development, we focus on the macroeconomic variables produced endogenously by the model to conclude that, as postulated by Kaldor (1957):

- Capital per worker shows steady growth (refer to Figure 5);
- The average growth rate of output per worker is positive and relatively constant over time (refer to Figure 6).

Nevertheless, and contrary to Kaldor's facts of growth:

- The shares of income devoted to capital and labor show trends, thus not fluctuating around constant means (refer to Figure 7);
- The real rate of return to capital shows an upward trend (refer to Figure 8).

Figure 5: Log capital per worker

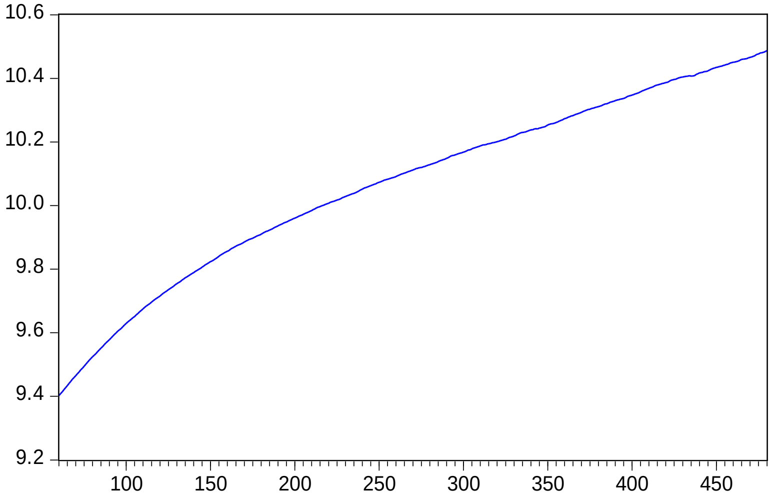


Figure 6: Growth rate of productivity (output per worker)

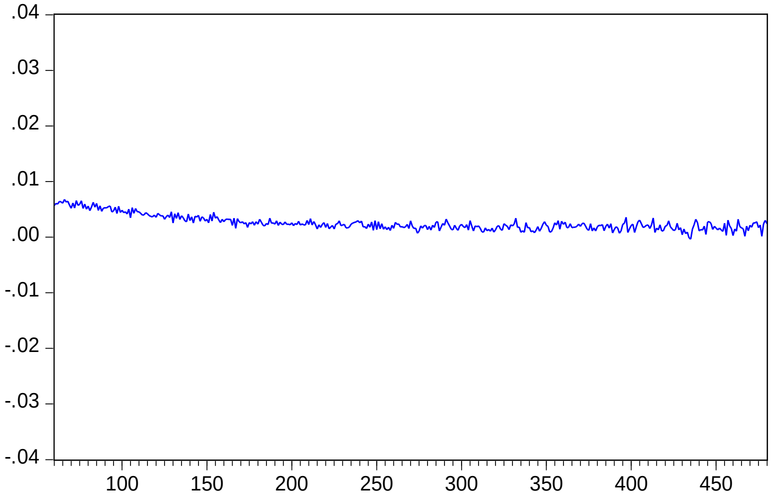


Figure 7: Share of income devoted to capital and labor

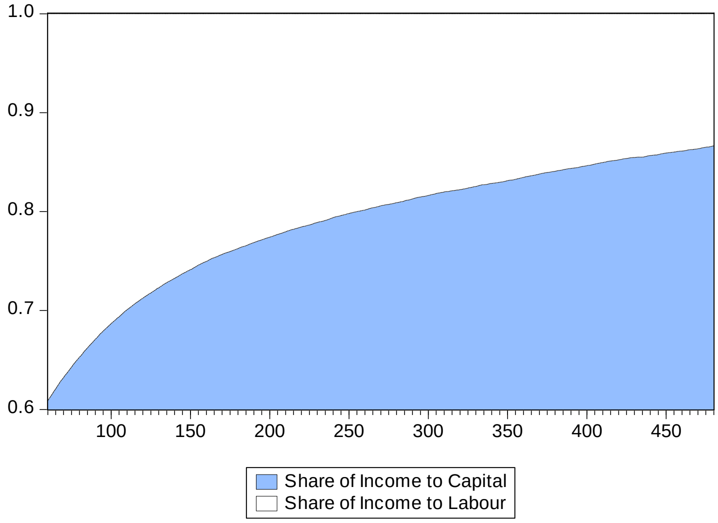
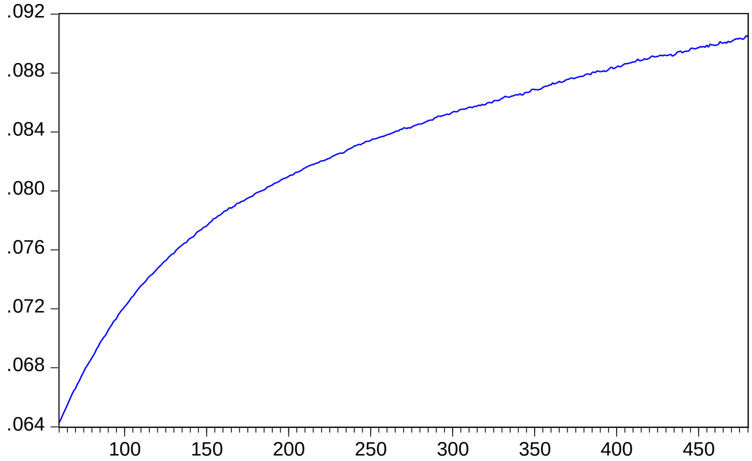


Figure 8: Real rate of return to capital



3 Simulation and results

As pointed out in the introduction of the paper, this study focuses on developing a model that replicates the conjunct dynamics of a financial market, a banking system, and the real economy, mimicking several stylized facts of the latter and grasping, to a certain extent, the implications of banking regulation in economic performance.

Specifically, and based on the model described in Section 2, policy experiments are designed to answer the following seminal questions:

1. Are banks key drivers of economic performance?
2. What effect do different micro-prudential regulations have in economic growth?
3. Are macro-prudential policies effective promoters of financial stability?

In line with the methodology used to calibrate the model (refer to Section 2.3), each experiment encompassed 1000 simulations of 40 years (i.e., 480 time steps).

3.1 The role of banks

From the theoretical standpoint described in Section 1, and following the seminal paper of Diamond and Dybvig (1983), banks play a crucial role in economic growth by pooling liquidity from depositors (who prefer to have their savings placed in liquid instruments) and channeling the funds to firms (who require long-term, large-sum investments in order to generate returns in the future).

This view is corroborated by the policy experiments of our model. To assess the importance of banks in economic performance, a comparison was made between the most important economic aggregates resulting from simulated economies with and without banks. Specifically, we compare the model results in the baseline calibration with the model results in a scenario in which banks are shut down. Operationally, the behavior of banks was adjusted in order to require from any loan applicant a financial autonomy ratio greater than 100% (which is naturally not feasible). In this scenario banks were thus turned into mere operators of the economy's payments systems (which are, nevertheless, a crucial infrastructure of modern economies).

From the results reported in Table 5 it is clear that the existence of banks improves economic development. Indeed, all measures reveal a manifest degradation in median performance when banks are suppressed.

The reason for these phenomena is related with the inner workings of the modelled economy. Since no aggregate equilibrium relationship is forced between the agents' actual and expected demand, out-of-equilibrium dynamics are created at the level of each specific agent. Since there are no market-clearing mechanisms, the economy spontaneously self-organizes toward a state in which demand persistently exceeds supply. Economic growth in our model is thus a function of the firms' ability to increase production capacity through investment. The inexistence of banks is a clear obstacle to this process, since in this scenario companies' investment capacity is limited to their ability to endogenously generate capital. As such, the capacity of the economy to meet aggregate demand is severely hampered when there is no banking system, as reflected in the difference of the output gap (here defined as the difference between potential GDP if all demand was met and actual GDP) in both scenarios (3.31% in the baseline calibration versus 7.35% in the setting with no banks).

This mechanism is also the reason why GDP volatility is less in environments where credit institutions are shut down (0.86% in the baseline calibration against 0.59% in the setting with no banks). The fact that capital investments cannot be leveraged through bank financing means that production responds more slowly to increases in expected demand. Firms adjust more slowly and smoothly to increases in consumption and exports, which in turn reduces GDP's volatility.

In addition, in our baseline calibration firm failures are mostly attributable to potential gaps between expected and actual demand. These gaps can create an unexpected shock to profits which, associated with firm's leverage, may render institutions unable to meet their commitments. It would thus be expected that an economy without banks (and thus without credit) would result in lower default rates.

In a very interesting result, however, the default rate of firms is higher under the scenario in which credit institutions are shut down (1.49% in the baseline calibration against 5.20% in the setting with no banks). This curious feature of the model is attributable to the fact that firms face a monthly capital depreciation rate. Without banks to finance reinvestment, firms are often unable to secure the amount of cash needed to prevent capital erosion. Ultimately, the depreciation of

Table 5: Banks vs. no banks

	Banks	**No Banks**
Output gap	3.31%	7.35%
GDP volatility	0.86%	0.59%
GDP autocorrelation coefficient	0.93	0.92
Firms' default rate	1.49%	5.20%
Banks' default rate	0.57%	–

capital reduces firms' production capacity to the extent of making them unable to achieve break-even, in which case firms default due to their inability to pay wages. Based on this, it is possible to conclude that banks not only foster growth, they also contribute to the maintenance of the current level of wealth as measured by an economy's production capacity.

3.2 The impact of micro-prudential policies

The impact of micro-prudential regulation is gauged by considering alternative scenarios in which banks are either riskier or safer than in our baseline calibration. In the risky scenario:

- Loan underwriting policies are looser. By imposing a minimum financial autonomy ratio of just 0.3, banks implement lenient credit quality requirements when assessing firms and consumers, thereby significantly increasing the universe of loan-eligible agents;
- The required capital adequacy ratio is diminished to just 2%, which significantly increases the capacity of credit institutions to provide loans.

In the safe scenario:

- Loan underwriting policies are stricter. By imposing a minimum financial autonomy ratio of 0.9, banks implement stricter credit quality requirements when assessing firms and consumers, thereby significantly decreasing the universe of loan-eligible agents;

- The required capital adequacy ratio is augmented to 15%, a much more credit-constraining scenario than the one imposed in the baseline calibration (8%).

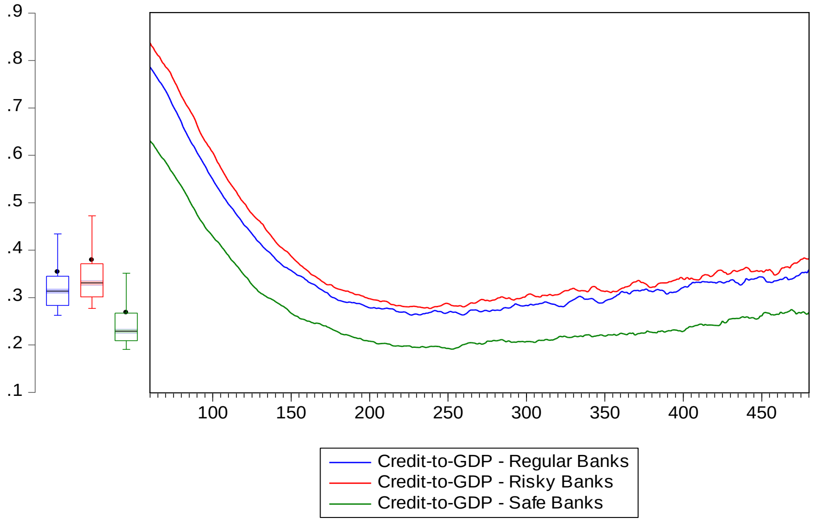
As Table 6 clearly reveals, aggregate macroeconomic performance deteriorates as banks become safer. Indeed, the median output gap is greater in scenarios in which prudential policies are looser (the output gap stands at 3.26% in the risky scenario, which compares to 3.31% in the baseline calibration and 3.66% in the setting with safe banks). This result corroborates our earlier conclusions, according to which increased credit availability improves the creation of value by increasing the speed at which supply is able to meet surges in demand. In the same vein, it is also clear that the mechanisms contributing to GDP volatility are magnified when credit is less constrained.

On the other hand, it is interesting to recognize that the default of firms responds in a non-monotonic way to changes in the micro prudential framework. While the scenario with safe banks displays the highest default rate (1.83%), thus confirming that credit is important for firms to stay afloat in periods of low demand, the scenario with risky banks is not the best performer (the default rate is 0.17% higher than in the baseline calibration). This result suggests that there is an inflection point after which less credit constraints actually contribute to a degradation of firms' financial robustness. Beyond a certain indebtedness level, and in a manifestation of the financial accelerator effect postulated by Bernanke et al. (1996), increased firm leverage (see Figure 9) makes credit institutions more likely to face distress (due to increased client bankruptcies and credit losses), which in turn increases companies' likelihood of failure (due to foreclosures by failing banks and credit rationing by low-capitalized institutions).

Table 6: Safe banks, regular banks and risky Banks

	Safe banks	**Regular banks**	**Risky banks**
Output gap	3.66%	3.31%	3.26%
GDP volatility	0.74%	0.86%	1.19%
GDP autocorrelation coefficient	0.93	0.93	0.94
Firms' default rate	1.83%	1.49%	1.66%
Banks' default rate	0.57%	0.57%	1.14%

Figure 9: Credit-to-GDP ratio (cross-run average)



Also remarkable is the fact that firm defaults and the output gap do not move in tandem with each other. Given that new entrants are smaller than incumbent companies, it would be expected that more firm failures would entail decreased economic performance. This thesis is repudiated by the risky scenario, in which the greatest number of defaults coincides with the lowest median output gap. Such a result clearly indicates that firm failures are less likely to slow down the economy when firms have easy access to credit since this source of financing allows entrants to quickly catch up with production requests.

As expected, the decrease in the capital adequacy ratios of banks is automatically reflected in increased default rates among credit institutions. On the other hand, increased capital ratios are not automatically reflected in safer institutions, as seen by the fact that the median bank bankruptcy rate is virtually the same in the scenarios with safe and regular banks. This result indicates that micro-prudential policy entails calibration risk: while increasing capital requirements increases the loss-absorbency capacity of banks, it also decreases their ability to endogenously generate capital through profits.

In addition, and despite the fact that bank and firm failures are much more numerous in the risky scenario than in the baseline setting, value-creation improves. This phenomenon stems from the fact that there is an important circuit breaker that prevents the modelled economy from suffering terribly with bank-bankruptcies. The effective resolution of credit institutions, which are terminated immediately upon entering into technical insolvency (i.e., after displaying capital adequacy ratios below 0), means that depositors are not usually bailed-in to a great extent. As such, bank bankruptcies represent salutary events for the economy, which performs better after getting rid of “zombie-banks” that are not able to support investment because they do not comply with micro-prudential requirements.

Important insights can also be drawn from analyzing the behavior of the output gap in time. During the initial stages of the simulations, the gap between production capacity and aggregate demand is large in all scenarios (refer to Figure 10). In the setting with risky banks, the ability of firms to tap external sources of funds is translated into increased leverage and bankruptcies, which in turn contributes to a high output gap when compared to the remaining scenarios. However, as demand grows firms become able to sustain supplementary levels of debt. The output gap is thus closed much more quickly in the scenario in which banks are riskier.

In the long run, growth in the economy is ultimately capped by the growth of consumption and exports. Since the economy does not, on average, experience extraordinary spurs of growth, firms are usually able, in all scenarios and toward the end of the simulations, to raise the necessary capital (either endogenously or through bank financing) to meet demand. As such, the output gaps in different prudential frameworks tend to converge to the same value as time goes by.

In addition, and since labor costs are fixed in our model, the increase in the size of firms means that they are more easily able to sustain additional financing costs, which in turn is reflected in a substantial decrease in the number of firm defaults toward the end of the simulations (refer to Figure 11). A corollary of these results is that the role of banks (especially if risky) is more important when the economy is performing significantly below optimal levels (i.e., when the economy displays large output gaps).

Figure 10: Output gap (cross-run average)

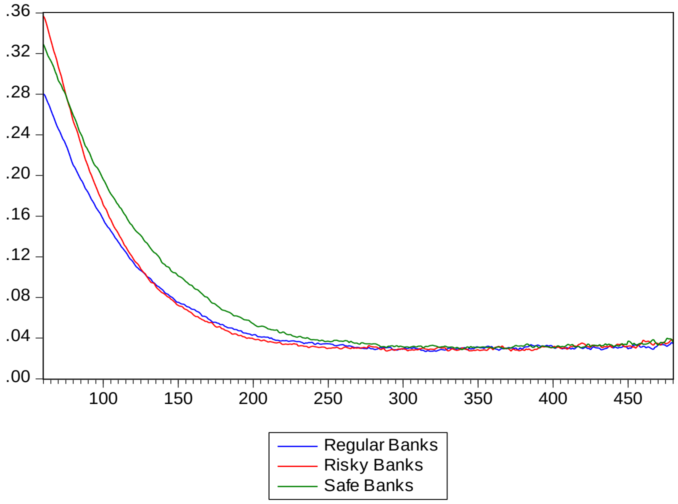
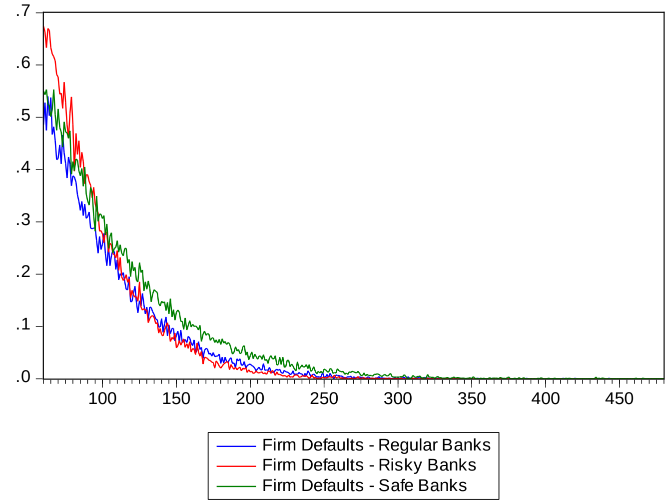


Figure 11: Firm defaults at each time step (cross-run average)



Finally, and on micro-prudential policy, it is also relevant to disentangle the effects of changes in the capital framework from modifications to the loan underwriting criteria of banks.

To analyze this, a sensitivity analysis is conducted. Starting from the model's baseline calibration, we vary, *ceteris paribus*, the minimum capital requirements of banks and the minimum financial autonomy ratios demanded by credit institutions from their customers. In order to guarantee that the stochastic properties of the model do not affect results, the simulation is performed using the same seed value for the random number generator. Figure 12 and Figure 13 display the differences in the output gap between each scenario and the baseline setting (depicted by the red line).

As can be seen, changes to the capital requirements have a dramatic impact on economic performance. In a clear validation of previous results, it is clear that the output gap is persistently higher (lower) when minimum capital requirements are greater (smaller).

On the other hand, it is also clear that changing the loan underwriting policies has a reduced impact on economic activity. In spite of this, and while there are no relevant differences in median performance between the baseline scenario (median output gap of 2.74%) and the scenario in which the minimum financial autonomy ratio is set at 30% (median output gap of 2.91%), it can be concluded that increasing the strictness of loan underwriting criteria tends to degrade macroeconomic performance (median output gap of 4.09%).

3.3 An exploratory analysis of macro-prudential policies

As already discussed, the recent financial crisis exposed a vicious circle in which difficulties in the banking system can prompt a recession in the real economy that then feeds back onto the financial sector. This phenomenon suggests that banks should increase their capital buffers in periods when systemic risk is greater.

The counter-cyclical buffer was designed to guarantee that the level of capitalization of the banking sector is consistent with the macroeconomic environment in which credit institutions operate. It should be enforced when the authorities acknowledge that the levels of credit in the economy are excessive and associated with systemic risk, and seeks to guarantee that banks have sufficient capital to withstand potential future losses in case of a bust.

Figure 12: Output gap under varying capital requirements (seed −204145716)

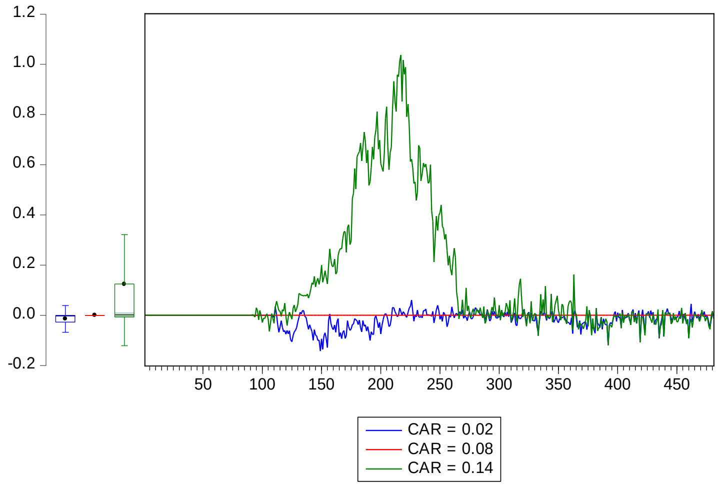
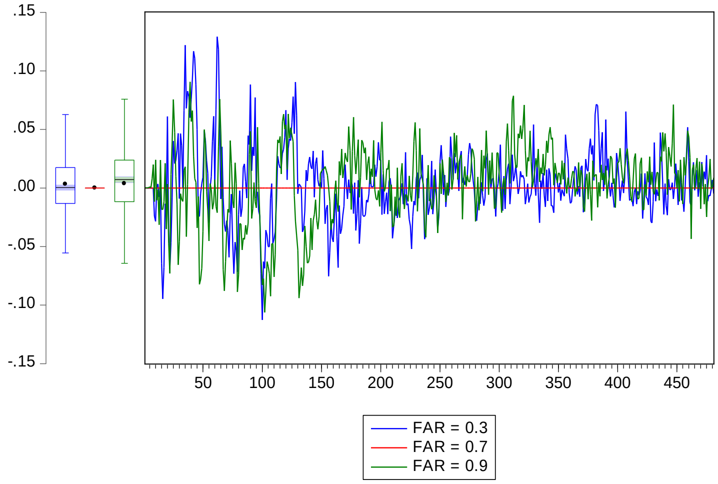


Figure 13: Output gap under varying financial autonomy requirements (seed −204145716)



To test the effectiveness of the counter-cyclical capital buffer, we depart from the baseline scenario by establishing a setting in which the regulator enforces an additional capital surcharge for banks whenever the credit-to-GDP ratio of the economy rises above 35% (which is the average value of the indicator in the baseline cross-run average time series). The buffer is then maintained for at least one year, with the possibility of extension should the economy's leverage remain above the threshold.

The results reported in Table 7 indicate that imposing a capital buffer of 2.5% (which is the value foreseen in Basel III) or 5% does not have a significant effect on the overall dynamics of the economy. The only visible benefit stemming from this measure is a very mild reduction in the median amount of firm defaults. However, and similarly to the results obtained in the "safe banks" scenario, this is not reflected in persistently lower output gaps (in fact, the opposite occurs).

As explained above, this is underpinned by the fact that firm defaults appear not to have a significant impact on economic growth (in spite of new entrants being smaller than incumbent firms). Indeed, increased access to credit allows new players to quickly catch up with production needs, a phenomenon that can completely offset the slowdown effect of firm bankruptcies.

In spite of this, it is possible to conclude that using credit-to-GDP ratios as a trigger to the implementation of the counter-cyclical capital buffer might be, if taken alone, an insufficient approach. The results of our model suggest that credit is most important when the output gap is greater. In practice this means that high levels of leverage may be beneficial if related with the need to close a large gap between the economy's supply and demand (i.e., when firms have abundant investment opportunities). Since the same level of leverage may be too high or too low depending on the current state of the economy, the establishment of a counter-cyclical capital buffer must also take into account the impact of credit-constraining measures in GDP growth and an assessment of the level of debt that can be sustained by the economy without causing the build-up of system-wide risk.

Table 7: Regular banks and banks subject to macro-prudential policies

	Banks subject to a CCB of 2.5%	Banks subject to a CCB of 5%	Regular Banks
Output gap	3.32%	3.36%	3.31%
GDP volatility	0.86%	1.08%	0.86%
GDP autocorrelation coefficient	0.92	0.96	0.93
Firms' default rate	1.43%	1.48%	1.49%
Banks' default rate	0.57%	0.57%	0.57%

3.4 Endogenizing bank failures

As described above, bank failures are a beneficial phenomenon in our baseline model. A bank that enters into resolution is naturally not complying with minimum capital requirements and is thus not allowed to make new loans. The assumption that this agent can be replaced by foreign investment by a credit institution that can finance economic activity from the outset could be one of the reasons why our model reveals improved economic performance with risky banks.

To address this shortcoming, we endogenize the cost of bank failures. As before, depositors of failed banks are still bailed-in, thus absorbing the losses of the institution and raising its capital to zero. Under the new setting, however, depositors further see a part of their deposits being converted into equity so that the new institution complies with minimum capital requirements (specifically, the capital adequacy ratio is set at 12% in excess of the minimum in each scenario).
Because bank recapitalization costs are now fully borne by depositors, the amount of cash available for agents to consume (in the case of consumers) and invest (in the case of firms) is reduced. The consequences of a bank failure for the economy are thus magnified in this setting.

As suggested by the data in Table 8, macroeconomic performance is clearly worsened when costly bank failures are built into the model. However, the scenario in which banks are risky is still clearly the best performer within the scenarios under analysis. This result thus suggests that the benefits of increased credit availability are able to outstrip the costs stemming from a higher probability of bank failures.

Table 8: Safe Banks, Regular Banks and Risky Banks with endogenized bank failures

	Safe banks	Regular banks	Risky banks
Output gap	3.88%	3.35%	3.27%
GDP volatility	0.76%	0.90%	1.11%
GDP autocorrelation coefficient	0.94	0.93	0.94
Firms' default rate	1.89%	1.43%	1.66%
Banks' default rate	0.57%	0.57%	1.14%

When comparing the baseline scenario with the scenario in which bank bankruptcy is more costly, it is also possible to conclude that the magnitude of the degradation of macroeconomic performance is less in the setting with risky banks. Indeed, the difference in the output gap between the baseline scenario and the current setting is much lower in the setup in which the economy is less credit-constrained (change of +0.01% for risky banks, which compares with +0.22% for safe banks). This result once again corroborates the view that increased credit availability is generally beneficial for the economy, even when bank bankruptcies are extremely costly.

Finally, it is also important to note that this exercise demonstrates the importance of effective bank resolution. By demonstrating that costlier bank bankruptcies have a detrimental effect on economic performance, the experiment simultaneously shows that mechanisms that promote the effective resolution of banks by mitigating losses among creditors are of pivotal importance for economic growth.

4 Concluding Remarks

In this study we developed an agent-based computational model through which an exploratory analysis of the economic role of banks under different prudential frameworks was conducted. In a context in which mainstream economic knowledge has been strongly discredited by the subprime mortgage crisis and the ensuing great recession, we provide a valuable methodological contribution to the field of banking research by developing a rich, yet tractable, agent-based computational model that is able to replicate the conjunct dynamics of a financial market, a banking system and the real economy.

A calibrated version of the model is shown to provide a tenable account of some of the most important stylized facts of U.S. business cycles and economic growth. In a series of policy experiments we demonstrate that the model constitutes a powerful laboratory in which to investigate several of the seminal questions that have recently re-emerged as major concerns for policy-makers:

1. Are banks key drivers of economic performance?
2. What impacts do different micro-prudential regulations have on economic growth?
3. Are macro-prudential policies effective promoters of financial stability?

In this respect, our innovative approach gives rise to several results of general qualitative interest, shedding new light on some of the conventional notions underpinning the study of banks and bank prudential policies. Specifically, our analysis suggests that banks are indeed key drivers of economic performance. Through their lending activity, credit institutions are able to facilitate investment, thereby promoting growth and alleviating the effect of shocks.

Our investigation also demystifies some of the canons behind micro-prudential regulation, which has recently leaned in favor of ever-increasing capital requirements. In particular, the experiments conducted show that:

i. Stricter capital requirements have detrimental effects on aggregate macroeconomic performance by indirectly giving rise to credit rationing phenomena;
ii. Credit availability, to the extent that it is not excessive, prevents the depletion of firms' capital and, as such, contributes to a reduction in corporate bankruptcies;
iii. Stricter capital requirements are not always conducive to a reduction of bank defaults due to the impact of this measure on the profitability levels of banks.

Our study also fails to find evidence in support of the implementation of counter-cyclical prudential tools. It does demonstrate, nonetheless, that credit availability is more important when the economy is operating far from optimal levels (i.e., when the output gap is larger). By showing that high levels of economic leverage may be beneficial when paired with large output gaps, this result implicitly demonstrates that the credit-to-GDP ratio is not an accurate stand-alone trigger for the implementation of the counter-cyclical buffer.

Finally, the results of our model also highlight the vital importance of effective resolution frameworks. Such mechanisms significantly contribute to macroeconomic stability by ensuring that “zombie-banks” are shut down in a timely fashion and that depositors are not exposed to extreme losses in case of bail-in.

These insights are of great interest to the regulatory authorities, especially in what concerns the negative impact that higher regulatory capital requirements tend to have on macroeconomic growth. Indeed, our conclusions suggest that the introduction of Basel III/CRD IV, in which capital requirements are increased and counter-cyclical buffers introduced, may in the end contribute to the worsening of the economic environment. On the other hand, the implementation of the Banking Recovery and Resolution Directive, which seeks to overcome several of the shortcomings in the existing tools available to EU Authorities for preventing or tackling the failures of banks, is strongly supported.

The pioneering analysis conducted in this study is, however, too stylized to guide policy-making on its own. In many ways, our model constitutes an idealized environment in which (i) firm bankruptcy costs are not fully built into the model and, more importantly, (ii) there is no interbank market and hence no interconnectedness between credit institutions. While not invalidating the fact that our framework provides a fruitful benchmark for analyzing the properties of banking systems, these limitations cannot be neglected.

Going forward there are thus a number of ways in which this work could be extended. First, the costs associated with firm bankruptcies could be fully endogenized. As it stands, the model builds on the premise that companies can be replaced through foreign investment. Although the economy is still affected by firm defaults because new entrants are assumed to be smaller than incumbents, the current architecture of the model offsets the negative effects of this phenomenon.

Second, an interbank market could be integrated. As a result, the agent-based framework developed here could be used to study the “domino effect”, one of the main drivers behind the recent vicissitudes of financial markets. Specifically, modeling an interbank market would allow the study of its potential to act as contagion channel for liquidity and solvency crises. Given that our framework is a stylized, yet substantive representation of a real economy, this would complement recent research efforts that have sought to analyze and estimate the effects of credit networks on macroeconomic performance (Delli Gatti et al., 2010; Tedeschi et al., 2012).

As a concluding note, we reiterate the exploratory nature of our work while concomitantly accentuating its methodological contribution to the field of banking research, materialized in the development of a model that provides insights that could otherwise be elusive if scrutinized under the lens of other, more conventional approaches.

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Appendix

Table A1: ADF test (no intercept or trend)
Cross-run average time series of log GDP – Baseline calibration

Null Hypothesis: GDP has a unit root
Exogenous: None
Lag Length: 9 (Automatic - based on SIC, maxlag=17)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		1.438923	0.9629
Test critical values:	1% level	-2.570466	
	5% level	-1.941578	
	10% level	-1.616194	

*MacKinnon (1996) one-sided p-values.

Augmented Dickey-Fuller Test Equation
Dependent Variable: D(GDP)
Method: Least Squares
Date: 02/26/15 Time: 21:17
Sample: 60 480
Included observations: 421

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDP(-1)	6.26E-06	4.35E-06	1.438923	0.1509
D(GDP(-1))	0.166225	0.048820	3.404837	0.0007
D(GDP(-2))	0.327729	0.049231	6.656964	0.0000
D(GDP(-3))	-0.155027	0.051637	-3.002276	0.0028
D(GDP(-4))	0.054448	0.053077	1.025835	0.3056
D(GDP(-5))	0.178412	0.052348	3.408165	0.0007
D(GDP(-6))	0.037580	0.052991	0.709172	0.4786
D(GDP(-7))	0.045778	0.052473	0.872409	0.3835
D(GDP(-8))	0.155157	0.049588	3.128924	0.0019
D(GDP(-9))	0.139903	0.049362	2.834199	0.0048

R-squared	0.809321	Mean dependent var	0.002565
Adjusted R-squared	0.805146	S.D. dependent var	0.001343
S.E. of regression	0.000593	Akaike info criterion	-12.00004
Sum squared resid	0.000144	Schwarz criterion	-11.90402
Log likelihood	2536.009	Hannan-Quinn criter.	-11.96209
Durbin-Watson stat	2.021119		

Table A2: ADF test (intercept and trend)
Cross-run average time series of log GDP – Baseline calibration

Null Hypothesis: GDP has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 3 (Automatic - based on SIC, maxlag=17)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-10.68448	0.0000
Test critical values:	1% level	-3.980006	
	5% level	-3.420533	
	10% level	-3.132959	

*MacKinnon (1996) one-sided p-values.

Augmented Dickey-Fuller Test Equation
Dependent Variable: D(GDP)
Method: Least Squares
Date: 02/26/15 Time: 21:18
Sample: 60 480
Included observations: 421

Variable	Coefficient	Std. Error	t-Statistic	Prob.
GDP(-1)	-0.011720	0.001097	-10.68448	0.0000
D(GDP(-1))	0.090017	0.047722	1.886286	0.0600
D(GDP(-2))	0.230838	0.046490	4.965323	0.0000
D(GDP(-3))	-0.186049	0.047606	-3.908075	0.0001
C	0.170527	0.015883	10.73666	0.0000
@TREND("60")	1.97E-05	2.02E-06	9.742456	0.0000

R-squared	0.821892	Mean dependent var	0.002565
Adjusted R-squared	0.819746	S.D. dependent var	0.001343
S.E. of regression	0.000570	Akaike info criterion	-12.08725
Sum squared resid	0.000135	Schwarz criterion	-12.02963
Log likelihood	2550.366	Hannan-Quinn criter.	-12.06448
F-statistic	383.0099	Durbin-Watson stat	2.005924
Prob(F-statistic)	0.000000		

Table A3: ADF test (intercept and trend)
Example time series of log GDP (seed -397426811) – Baseline calibration

Null Hypothesis: SEED___397426811_ has a unit root
Exogenous: Constant, Linear Trend
Lag Length: 1 (Automatic - based on SIC, maxlag=17)

		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-1.513395	0.8240
Test critical values:	1% level	-3.977372	
	5% level	-3.419250	
	10% level	-3.132200	

*MacKinnon (1996) one-sided p-values.

Augmented Dickey-Fuller Test Equation
Dependent Variable: D(SEED___397426811_)
Method: Least Squares
Date: 02/18/15 Time: 19:51
Sample (adjusted): 3 480
Included observations: 478 after adjustments

Variable	Coefficient	Std. Error	t-Statistic	Prob.
SEED___397426811_(-1)	-0.014250	0.009416	-1.513395	0.1308
D(SEED___397426811_(-1))	-0.147429	0.027361	-5.388184	0.0000
C	13995.62	11664.01	1.199898	0.2308
@TREND("1")	55.72262	24.32668	2.290598	0.0224

R-squared	0.075482	Mean dependent var	2217.037
Adjusted R-squared	0.069631	S.D. dependent var	38776.71
S.E. of regression	37402.32	Akaike info criterion	23.90519
Sum squared resid	6.63E+11	Schwarz criterion	23.94008
Log likelihood	-5709.339	Hannan-Quinn criter.	23.91890
F-statistic	12.89992	Durbin-Watson stat	1.137362
Prob(F-statistic)	0.000000		

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The Editor