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Combining Monetary Policy and Prudential Regulation: An Agent-Based Modeling Approach

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This paper explores the interaction between monetary policy and prudential regulation in an agent-based modeling framework. Firms borrow funds from the banking system in an economy regulated by a central bank. The central bank carries out monetary policy, by setting the interest rate, and prudential regulation, by establishing the banking capital requirement. Different combinations of interest rate rule and capital requirement rule are evaluated with respect to both macroeconomic and financial stability. Several relevant policy implications were drawn. First, the efficacy of a given capital requirement rule or interest rate rule depends on the specification of the rule of the other type it is combined with. More precisely, less aggressive interest rate rules perform better when the range of variation of the capital requirement is narrower. Second, interest rate smoothing is more effective than the other interest rate rules assessed, as it outperforms those other rules with respect to financial stability and macroeconomic stability. Third, there is no tradeoff between financial and macroeconomic stability associated with a variation of either the capital requirement or the smoothing interest rate parameter. Finally, our results reinforce the cautionary finding of other studies regarding how output can be ravaged by a low inflation targeting.

Keywords: Agent-based modeling; monetary policy; financial stability; prudential Regulation..

JEL Codes: E52; G18; C63.

Combining monetary policy and prudential regulation: An agent-based modeling approach*

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Abstract

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1. Introduction

The 2008 financial crisis promoted a revival of the debate on the interaction between the real and financial sectors. Although some arguments, such as the financial accelerator proposed by Bernanke and Gertler (1995), had already pointed out the existence of transmission channels from one sector to the other, the crisis suggested that such interlinks could be much more complex than initially thought. The recent financial crisis made it clear that small disturbances in one sector, through essentially nonlinear relationships, could be amplified and spread across both sectors. Indeed, although there is no consensus regarding the roots of the recent financial turmoil, it is widely accepted that it has crossed the border of the financial sector, bringing heavy losses to the real economy. [1]

Before the crisis, the reigning view concerning macroeconomic policy was that monetary policy and prudential regulation could pursue their goals – macroeconomic and financial stability, respectively – acting independently, without any need of coordination. According to this dominant paradigm, monetary policy based on inflation targeting and flexible exchange rates and financial regulation grounded on microprudential measures would both accomplish their independent objectives (Canuto and Cavallari 2013).

More recently, the balance started to be tipped in favor of a more harmonious interaction between monetary policy and prudential regulation. In fact, through linkages between real and financial variables, one policy may affect the other's target, sometimes even in an undesirable way. For instance, by pursuing macroeconomic stabilization in a recession scenario, monetary policy may reduce the interest rate. However, low interest rates may lead to less banks' incentive to monitor borrowers, over-leverage in banks and the bearing of higher risks by agents in order to achieve higher returns, bringing threats to financial stability (IMF 2013). Hence, the stand-alone execution of policies may lead to unsatisfactory outcomes.

[1] While the role of financial disturbances in generating the 2008 financial crisis has been emphasized in most of the related studies, many authors highlight the importance of previous real sector imbalances in this process. For instance, the mismatch between real wages and productivity growth generated a structural flaw in aggregate demand in the U.S. economy prior to 2007 (Setterfield, 2012). The relationship between income inequality and the recent financial crisis (e.g., through the fueling of financial bubbles) has also been extensively discussed (see, e.g., Palley, 2016; Skott, 2013).

To explore the issue of such policy coordination, existing macroeconomic models should be endowed with an attribute which proved to be important in the recent financial crisis: the ability to deal with nonlinear interdependencies between real and financial variables. In the case of *Dynamic Stochastic General Equilibrium* (DSGE) models, the main workhorse of most central banks, this is done through the incorporation of financial frictions (BCBS 2012). This allows the study of optimal combinations between monetary policy and prudential regulation within the DSGE framework, as has been done recently by some researchers (e.g., Agénor et al. 2013; Beau et al. 2012; Goodhart et al. 2013; Lambertini et al. 2013).

Nonetheless, DSGE models have some inherent characteristics which limit their usefulness to the assessment of policy actions. As discussed above, a key element to grasp the occurrence of financial crashes is an understanding of nonlinear feedbacks among financial and real variables. Nevertheless, the incorporation of nonlinearities in DSGE models is quite limited, as they are usually solved through log-linearization around a unique steady state. Furthermore, the embodying of some endogenous elements responsible for the propagation of the crisis, as boundedly rational behavior and inefficient markets, is a real challenge in DSGE models, due to their assumption of forward-looking fully rational behavior (Canuto and Cavallari 2013). Indeed, in these models, risk is brought in by exogenous shocks. Additionally, the hypothesis of full rationality and optimizing behavior is even more unrealistic during financial crisis, as the validity of such hypothesis relies on historical relationships which no longer hold (Bookstaber 2012).

Another strategy has been the development of new approaches. One of the most promising alternative approach is the *Agent Based* (AB) modeling.[2] The AB modeling approach conceives of the economy as a *complex system*, defined by the presence of *emergent properties*, that is, an aggregate behavior remarkably distinct from the simple extrapolation of the individual units' behavior (Krugman 1996). In the AB modeling framework, agents (consumers, firms etc.) are rationally bounded computational entities. They interact with each other following simple behavioral rules, giving rise to nonlinear patterns. Such rules, grounded on incentives and information, may evolve

[2] By AB models we are referring to computational agent-based models. There are also models of heterogeneous interacting agents, solvable analytically through technics coming from statistical physics or Markov chains (Gallegatti and Kirman 2012).

according to their *fitness* – the payoff they provide to the agents adopting them. In this case, the model is called *evolutionary*. Once reasonable initial conditions and parameters of the model are set, the modeler can observe how the system evolves over time.

AB models have some advantages over DSGE models regarding the assessment of economic policy. According to Fagiolo and Roventini (2012), such advantages belong to two classes: theory and empirics. From the theoretical point of view, as they are not a priori required to be analytically solvable, they allow the relaxing of several simplifying assumptions (e.g., equilibrium and fully rational expectations) necessary for mathematical tractability. Their disengagement from analytical solvability allows them to cope with nonlinearities much better than DSGE models. This flexibility is at the root of their empirical advantage; it enables them to be much more realistic than DSGE models as regards inputs (assumptions more similar to the observed ones), as well as outputs (replication of stylized facts of interest).

Policy experiments with AB models are typically done in the following way. First, the AB model is designed to reproduce relevant stylized facts of the policy target (e.g., the price level). Then, it is gauged how the implementation or changes in some policy parameter (e.g., the interest rate) impact on the behavior of such variable (Fagiolo and Rovetini 2012). The possibility of implementing a wide range of policy measures turns AB modeling very attractive for performing policy exercises, as has been done extensively in recent years.[3]

The aim of this paper is to study the interaction between monetary policy and prudential regulation in an AB modeling framework. In the model proposed here, firms borrow funds from the banking system in an economy regulated by a central bank. The central bank is responsible for carrying out monetary policy, by setting the interest rate, and banking prudential regulation. Among the multiple tools available for prudential regulation, we deal with a specific one in this paper, namely, the capital requirement through the setting of a cyclical buffer. Different combinations of interest rate and capital requirement rules are carefully evaluated with respect to macroeconomic and financial stability. The former depends negatively on output and price volatility and the latter is measured by the non-performing loans (hereafter, NPL)-to-credit ratio. While

[3] See the excellent review in Fagiolo and Roventini (2012).

monetary policy employs Taylor-type interest rate rules, the capital requirement rules involve the establishment of a cyclical component, as proposed in the Basel II agreement. Our purpose is to gain qualitative insights on suitable combinations between monetary policy and prudential regulation.

AB modeling has been extensively applied by researchers to analyze the impacts of monetary policy on the economy. Usually, effects of monetary policy are explored through changes in the interest rate, as in Dosi et al. (2013). In some studies (e.g., Delli Gatti et al. 2010; Raberto et al. 2008; Mandel et al. 2010; Riccetti et al. 2013c), such changes are driven by Taylor-type rules. Prudential regulation has also been the object of study of AB models. Teglio et al. (2012) and Cincotti et al. (2012), for instance, study the impact of capital requirement rules on the economy employing the EURACE model.[4] Neuberger and Rissi (2012) show that regulatory policy may be effective in homogeneous or bank-based financial systems, depending on the stability measure used. Krug et al. (2015) develop a stock-flow consistent AB model to assess the effects of the main components of Basel III on financial stability. Starting from a decentralized matching AB macroeconomic model, Riccetti et al. (2013a) find a positive effect of the implementation of a capital requirement buffer.

Nonetheless, studies devoted to test different combinations of monetary policy and prudential regulation within the AB modeling framework are scarce. As far as we know, there are not many AB models explicitly intended to explore this issue. Krug (2015) presents elements in favor of the Tinbergen's principle by arguing that the "leaning against the wind" monetary policy seems to have no impact on financial stability, which can be reached through macroprudential regulation. A slightly different view is proposed by Popoyan et al (2017), according to which the "leaning against the wind" monetary policy contributes to the stability of the economy as a whole. Furthermore, the authors point that macroprudential tools have limited impact on inflation, but reduce unemployment and output gap. Simulations performed by van der Hoog (2015) suggest that the best scenario regarding financial stability is achieved by combining the use of a non-risk-weighted total capital ratio with the full credit rationing of all financially unsound firms. Somehow similar exercises were conducted mainly through the use of DSGE models, as referenced above. A noteworthy exception is

[4] EURACE is a large-scale, multi-sector agent-based model and simulator, which is under development since 2006 within an EU-funded research grant (Cincotti et al. 2011).

Barnea et al. (2015), which develop an overlapping-generations model to analyze the interaction between these policies. However, we believe that AB models, due to their greater flexibility to deal with interacting agents and nonlinearities, can shed new and relevant light on this issue.

In addition to this introduction, this paper has four other parts. Section 2 outlines the model, while simulation results corresponding to the baseline case are shown in Section 3. Meanwhile, Section 4 contains an assessment of various combinations of monetary policy and prudential regulation, considering their performance with respect to both macroeconomic and financial stability. Concluding remarks are presented in the last section.

2. Structure of the model

The model is composed by four groups of agents: i) firms, which produce consumption goods, ii) the banking system, which provides credit to firms and receive deposits from them, iii) households (workers and shareholders), which consume firms' goods, and iv) the government, which is in charge of setting the base interest rate and the capital requirement ratio (through the central bank) and carries out fiscal policy.

The model herein has several ingredients of other models, such as Delli Gatti et al. (2010) and Dosi et al. (2013), in addition to several novel features. Indeed, our purpose is not to contribute methodologically to the literature on the agent-based economic modeling framework, but rather to explore a specific issue (the coordination between monetary policy and prudential regulation) within such framework. The main feature of the model herein is the supply/demand mutual restriction. An individual firm's sales are a fraction of aggregate demand, but constrained by its own production. Hence, an individual firm's output can be either equal or lower (engendering unfulfilled demand) or higher (engendering unsold production) than the firm's share in aggregate demand. It is supposed that firms operate in an imperfect information environment, which allows them to set different prices. Market shares are a function of the corresponding markups: firms setting relatively lower markups increase their market share. Firms with negative net worth are expelled from the model, and any bankrupt firm is replaced by a new one.

On the financial side, firms' demand for credit with the banking system follows the "dynamic trade-off theory" proposed by Riccetti et al. (2013b), meaning that firms have a long-run leverage target. Firms' credit demand is fulfilled following a ranking based on their net worth. The banking system sets a different interest rate to each firm according to its own leverage and that of the firm.

As it turns out, there is interdependence among the individual firms' financial robustness, which operates through two channels. The first one is the banking credit. If a firm goes bankrupt, the banking system's net worth shrinks. As the maximum total credit is a multiple of the banking system's net worth, the available credit will be lower in the next period, thus eventually preventing other firms from producing more. The second such channel is a demand externality. By producing less, firms reduce aggregate demand, thus affecting the other firms' revenues and profits.

The following subsections detail the behavior of each component of the model.

2.1. Accounting identities

There is an aggregate consistency between assets, liabilities and the financial resources circulating among the components of the model. Firms' resources are composed by net worth, NW, and loans, B. The banking system's assets are formed by loans, B, and cash, R, which sum is equal to its net worth, NW^B, plus deposits, D. Shareholders receive a fraction of firms' and banking system's profits as dividends, A. As in Delli Gatti and Desiderio (2015), we assume that firms' loans take the form of inside money – that is, deposits in the banking system – so that aggregate deposits are equal to aggregate loans. All agents (households, firms, and the banking system) keep their liquid resources in form of cash R. These accounting relationships are all represented in Table 1.[5]

The flow of nominal funds is displayed in Table 2. The aggregate wage bill, given by wL, where w is nominal wage and L is hired labor, is paid by firms and received by workers. A share of nominal profits is received by shareholders as

[5] Tables 1 and 2, in which the representation of a stock-flow consistent (SFC) model is displayed, are simplified versions of, respectively, Tables 1.3 and 1.2 in Godley and Lavoie (2007). The government net worth with a plus sign (i.e., a negative government net worth) can be interpreted as "net government advances" to the other agents (Dos Santos and Zezza 2008).

dividends. Nominal debt commitments, iB, where i is the nominal interest rate, flow from firms to the banking system. Nominal output, pY, where p is the price level and Y is the real output, is consumed by workers and shareholders. Government expenditure E is used to finance new firms or a new banking system. Finally, both firms and the banking system pay taxes to the government, in an amount equal to T^F and T^B, respectively.

Table 1: Balance-sheet matrix

	Banking system	Firms	Households	Govt.	Sum
Loans	$+B$	$-B$			0
Deposits	$-D$	$+D$			0
Cash	$+R^B$	$+R^F$	$+R^H$	$-R^G$	0
Net worth	$-NW^B$	$-NW^F$	$-NW^H$	$+NW^G$	0
Sum	0	0	0	0	0

Table 2: Flow of funds

	Firms	Banking system	Households	Government	Sum
Consumption	$+pY$		$-pY$		0
Wages	$-wL$		wL		0
Dividends	$-A^F$	$-A^B$	A		0
Debt commitments	$-iB$	iB			0
Govt. expenditures	$+E^F$	$+E^B$		$-E$	0
Taxes	$-T^F$	$-T^B$		T^F+T^B	0
Change in Loans	$+\Delta B$	$-\Delta B$			0
Change in Deposits	$-\Delta D$	$+\Delta D$			0
Change in Cash	$-\Delta R^F$	$-\Delta R^B$	$-\Delta R^H$	$+\Delta R^G$	0
Sum	0	0	0	0	0

2.2. Firms

A large number of firms, indexed by i=1,…, N, produce the consumption good using labor. It is assumed that firms operate under conditions of imperfect information in order to allow for price heterogeneity.[6] The relationship between the output of each firm, $Y_{i,t}$, and its available funds is represented by an increasing concave function, the so-called *financially constrained output function* (Delli Gatti et al. 2010):

$$Y_{i,t} = \alpha K_{i,t}^{\beta} \qquad (1),$$ [7]

where $\alpha > 0$ and $0 < \beta < 1$ are exogenously fixed (and uniform across firms) parameters, whereas $K_{i,t}$ comprises the stock of loans granted to the individual firm, $B_{i,t}^{S}$, and its net worth $NW_{i,t}$. Debt lasts for t_D periods. Therefore, the stock of debt is the sum of the flow of debts in the last t_D periods: $B_{i,t}^{S} = \sum_{t-t_D+1}^{t} B_{i,t}^{F}$. More details on how credit demand by firms is fulfilled will be provided in the next section. The production function of each firm is given by:

$$Y_{i,t} = \eta L_{i,t} \qquad (2),$$

where $L_{i,t}$ is the corresponding hired labor and $\eta \geq 1$ is the exogenously given labor productivity parameter, which is exogenously fixed. There is a perfectly elastic supply of labor, so that an individual firm can hire as much labor as it is willing to at the current wage. Considering (1) and (2), a firm will hire a quantity of labor given by $(\alpha/\eta)K_{i,t}^{\beta}$. It is assumed that the labor contract signed by firms and workers establish a minimum real wage. Therefore, there is a reasonable limit to the possibility that financially fragile firms improve their financial situation as a result of a sharp decline in real wage costs (recall that labor productivity is constant). The real wage, w_t / p_t, where w_t is nominal wage and p_t is the price level, has as lower bound a fraction ψ<1 of the

[6] On consumers' imperfect price knowledge, see, for instance, Rotemberg (2008).

[7] Equation (1) can be interpreted as (i) a simple rule of thumb to deal with bounded rationality and asymmetric information or (ii) the solution of an optimization problem of the firm, consisting in maximizing profits net of bankruptcy costs. More details can be found in Delli Gatti et al (2009).

initial real wage, w_0 / p_0. Therefore, the nominal wage, which is uniform across firms, is given by:

$$w_t = \begin{cases} w_{t-1} & if \quad \dfrac{w_{t-1}}{p_{t-1}} > \psi\left(\dfrac{w_0}{p_0}\right) \\ \psi p_{t-1}\left(\dfrac{w_0}{p_0}\right) & if \quad \dfrac{w_{t-1}}{p_{t-1}} \leq \psi\left(\dfrac{w_0}{p_0}\right) \end{cases} \qquad (3).$$

The nominal revenue of firm i at period t corresponds to a share $s_{i,t}$ of the aggregate nominal demand, C_t:

$$C_t = R^H_{t-1} + w_t L_t + \delta\pi_{t-1} - NW^{NF}_{t-1} - NW^{NB}_{t-1} \qquad (4).$$

Firms do not know either their market share $s_{i,t}$ or C_t. Aggregate demand corresponds to household cash (R^H_{t-1}) plus the dividends paid to shareholders in the previous period ($\delta\pi_{t-1}$) and the aggregate wage bill paid by the firms ($w_t L_t$), and minus any possible net worth of the new firms (NW^{NF}_{t-1}) and the new banking system (NW^{NB}_{t-1}). This feature of the model will be further described later. The parameter δ is the (constant) fraction of distributed profits, which is uniform across firms, and π is the aggregate nominal profit of firms and the banking system. Note that, for the sake of simplicity, we set the propensity to consume of households equal to 1.

The nominal profit of an individual firm is given by:

$$\pi_{i,t} = \min\left(p_{i,t}Y_{i,t}, s_{i,t}C_t\right) - w_t L_{i,t} - i_{i,t}B^S_{i,t} \qquad (5).$$

The first term in the expression above is the firm's revenue. It corresponds to the firm's share, $s_{i,t}$, of aggregate demand, which cannot be greater than firm's nominal production. Any remaining demand will be converted into household cash R^H_t. Goods depreciate completely in one period, thus every firm starts any period with no inventories. Firms' costs encompass labor costs, $w_t L_{i,t}$, and debt commitments, $i_{i,t} B_{i,t}^S$, where $i_{i,t}$ is the nominal interest rate charged on loans to an individual firm.

The individual price $p_{i,t}$ is determined by applying an individual markup, $\mu_{i,t}$, on the nominal wage.[8] The markup follows a behavioral rule, which is adapted from Dosi et al. (2013):

$$\mu_{i,t} = \mu_{i,t-1}\left(1+\phi\frac{s_{i,t-1}-s_{i,t-2}}{s_{i,t-2}}\right)\left(\frac{c_{t-1}}{c_{t-2}}\right) \qquad (6),$$

where $0<\varphi<1$ and c_t is the logarithm of aggregate demand. The above expression can be interpreted in the following way: if the firm loses market share, it will try to recover it by reducing its markup (as described in (7) below); moreover, a fall in aggregate demand also means lower profits, and the firm will adopt the same strategy in order to increase its market share and hence sustain its revenues. An individual firm's market share evolves according to the following rule inspired in Dosi et al. (2013):

$$s_{i,t} = s_{i,t-1}\left(1+\frac{\mu_t^M-\mu_{i,t-1}}{\mu_t^M}\right) \qquad (7),$$

where μ_t^M is the average markup at period t. Consequently, more price-competitive firms increase their market share.

Meanwhile, the dynamics of the individual firm net worth is given either by $NW_{i,t} = NW_{i,t-1} + (1-\delta-\tau)\pi_{i,t}$, if $\pi_{i,t}>0$, or $NW_{i,t} = NW_{i,t-1} + \pi_{i,t}$, otherwise. The parameters δ and τ are strictly in the interval between 0 and 1 and represent the dividends and tax rates, respectively. At any period, firms with a negative net worth are expelled from the model. For simplicity, the number of firms is kept constant. The sum of the market share of bankrupt firms is randomly distributed among entrant firms. Inspired in Riccetti et al (2015), we set the net worth of entrant firms as a function of current prices. The net worth of the new firms at period t is drawn from $N(1.5p_t, 0.3p_t)$.

[8] The assumption of markup pricing behavior goes in hand with robust survey data evidence (e. g., Fabiani et al. 2006).

The other attributes of entrant firms (leverage target and markup) are set according to the normal distribution $N(M_I, 0.2M_I)$, where M_I is the average value of the corresponding attribute of incumbent firms. These values take into account the minimum levels set in the Appendix.

2.3. The banking system

The amount of credit supplied by the banking system at any period is limited by the capital requirement set by the central bank, represented by the parameter *k*, where $0 < k < 1$, so that $B_t^S \leq NW_t^B / k$. Thus, the banking system is required by the central bank to keep a minimum net worth over the loans ratio equal to *k*. The maximum flow of credit at period t, B_t^F, is given by the difference between the maximum credit supply allowed and the funds already lent:

$$B_t^F = \max\left(NW_t^B / k - \sum_{t-t_D+1}^{t-1} B_t^F ,\ \ 0 \right) \qquad (8).$$

We suppose that the firms' capital structure is determined by the "dynamic trade-off theory" (Riccetti et al. 2013b). The "trade-off theory" (Jensen and Meckling 1976; Myers, 1977) is based on the trade-off between the costs and benefits of debt, implying that firms choose a leverage level, defined as the debt/net worth ratio. Riccetti et al. (2013b) proposed a "dynamic trade-off theory" (DTOT), according to which the adjustment of leverage towards a long-run target is governed by market frictions.[9] The credit demanded by firm i at period t is given by:

$$B_{i,t}^F = \max\left(l_{i,t}^* NW_{i,t} - \sum_{t-t_D+1}^{t-1} B_{i,t}^F ,\ \ 0 \right) \qquad (9).$$

In the equation above, $l_{i,t}^*$ denotes the desired leverage. Therefore, if the stock of debt of the firm in the beginning of the period is below the maximum it is willing to

[9] In fact, DTOT is also present in non-AB models, such as Flannery and Rangan (2006) and Frank and Goyal (2008, 2015).

borrow ($l^*_{i,t} NW_{i,t}$), the firm will ask for more loans. The desired leverage level evolves according to the following behavioral rule:

$$l^*_{i,t} = l^*_{i,t-1}\left(1+\lambda\frac{C_{i,t-1}-C_{i,t-2}}{C_{i,t-2}}\right) \qquad (10),$$

where $0<\lambda\le 1$ and $C_{i,t}=s_{i,t}C_t$ is the nominal demand of firm i at period t. The change in $l^*_{i,t}$ is constrained to the interval given by [-10%, +10%] per period, which is intended to impose enough cautiousness on agents' willingness to adjust their desired leverage. A rise in the demand for their output will lead firms to revise upwards their desired leverage: they will ask for more loans in order to produce more and realize higher sales. This rule can also be thought of as being driven by the very rationale of the banking system, as it is willing to lend to the more profitable firms.

Once B^F_t is established, firms are sorted in ascending order according to their target leverage and their credit demands are fulfilled until the limit given by B^F_t is achieved. The nominal interest rate charged on each individual firm, $i_{i,t}$, is established by applying a specific banking markup, $h_{i,t}$, on the base interest rate, $i^B(1+h_{i,t})$. Inspired in Delli Gatti et al (2010), we set the markup as

$$h_{i,t} = 0.5\left(l^B_t\right)^\gamma + 0.5\left(l_{i,t}\right)^\gamma \qquad (11).$$

In the preceding expression, i^B is the base interest rate set by the central bank, l^B_t is the bank leverage and γ is a positive risk premium parameter, $0<\gamma<1$. The first term implies that a sounder – that is, less leveraged – banking system will charge a lower interest rate. Besides, as implied by the second term, the interest rate paid by a firm is increasing in the firm's risk level, as measured by its leverage.

The nominal profit of the banking system is given by:

$$\pi^B_t = \sum\nolimits_{NW>0} i_{i,t}B^S_{i,t} - BD_t \qquad (12).$$

Therefore, the banking system receives the debt commitments of the firms with positive net worth and face a loss which is equal to the NPL, which follows the definition of bad debt presented in Delli Gatti et al. (2007): $BD_t = -\sum_{NW \leq 0} \max\left(NW_{i,t}, -B_{i,t}^S\right)$. For the sake of simplicity, we assume that the banking system pays no interest on deposits. Meanwhile, the banking system's net worth evolves according to either $NW_t^B = NW_{t-1}^B + (1 - \delta - \tau)\pi_t^B$, if $\pi_t^B > 0$, or $NW_t^B = NW_{t-1}^B + \pi_t^B$, otherwise. If the banking system has a non-positive net worth, it is replaced by a new one with a net worth equal to $NW_t^{NB} = k\sum_{NW > 0} B_{i,t}^S$.

2.4. The government

The government has a surplus Γ that evolves according to

$$\Gamma_t = \Gamma_{t-1} + \tau\left(\sum_{\pi > 0} \pi_{i,t} + \pi_t^B\right) - E_t \qquad (13).$$

Thus, the government revenues are the taxes collected from the firms and the banking system. Following Riccetti et al (2015), the government has a role in financing the new entrants. Its expenditures, E_t, will be the possible net worth of the new firms and of the new banking system, but keeping a surplus of at least 1% of the current real output:

$$E_t = \min\left\{\left(\Gamma_t - 0.01Y_t\right), \left(NW_t^{NF} + NW_t^{NB}\right)\right\} \qquad (14).$$

The residual net worth of new firms and new banking system, if any, will be subtracted from households' funds, as set in equation 4, up to the limit of 99% of their resources ($R_{t-1}^H + w_t L_t + \delta\pi_{t-1}$). If money to finance the new entrants is still needed, the government intervenes, incurring in a surplus smaller than its benchmark level (which can be even negative). It is important to stress that, as there is no injection of new resources in the model when new agents substitute the defaulted ones, we guarantee the stock-flow consistency of the model.

3. Simulations: the passive policy case

In this section, we run simulations considering that economic policy (monetary policy and prudential regulation) is merely passive. Therefore, the policy instruments k and i^B are exogenous rather than endogenously adjustable according to some adaptive rule. The parameters and initial conditions are reported in the Appendix.[10]

3.1. Baseline simulations

Figure 1 displays some basic statistics generated by the model, where we considered the average of 100 simulations. As a robustness check, we also performed simulations for β = 0.8. The dynamics of the system exhibit remarkably similar behavior, although the long-run levels differ widely. The real output, the nominal credit-to-output, the leverage and the NPL-to-credit ratio are much smaller when a β = 0.8 is considered.

There is no long-run growth, which is expected given the lack of any source of growth (e.g., increase in the number of firms or in labor productivity). Similarly to other agent-based models, the model herein is able to endogenously generate business cycles. When the economy is in the boom period, firms revise upward their leverage target, engendering higher levels of production and subsequent growth in aggregate demand. Firms' higher profits also keep the banking system in good financial shape, thus ensuring the necessary supply of credit. Such solid banking system' equity position pushes the interest rate down, while prices are pushed up. The credit expansion, combined with decreasing returns to net worth, spawns a greater credit-to-output ratio. In the descending phase, firms cut down markups to try to keep their market shares and avoid higher losses. The consequent shrink in the leverage level reinforces the reduction of output and aggregate demand. Eventually, some firms go bankrupt, which reduces the banking system's net worth. This can cause credit rationing, which creates a new source of instability.

[10] No calibration exercise on empirical data was performed, but using reasonable parameter values was always a major concern. In fact, most of the parameter values were drawn from existing studies (e.g., Riccetti et al. 2013b). We run simulations on a range of reasonable values and chose a set of parameters whose results were not counterintuitive on empirical grounds.

[Figures 1a-h around here]

Figure 1: Left-hand side, from top-down: Real output, nominal credit-to-output ratio, price level and real wage. Right-hand side, from top-down: leverage, leverage of eliminated firms, NPL-to-credit ratio and unsold production over output.

In all simulations, the real wage never reached its lower limit, which shows that workers do not suffer pronounced drops in their purchasing power. Consequently, nominal wages are kept constant. After an initial decline, the real wage experiences an increase and then stabilizes in a level at most 10% higher than the initial one. Therefore, the labor market dynamics, especially as it affects labor costs, does not have significant effects on firms' profitability.[11]

In order to bring some empirical validation to our model, we performed a comparison between the properties of the artificial series generated by our model and that of real time series, following the approach presented in Assenza et al (2015). Regarding the artificial data, we run 100 simulations of 2,000 periods, discarding the transient period comprised by the first 400 periods. We then used the HP-filter to calculate the cycle component in percentage value of the real product and the real consumption, considering that one period of the artificial series corresponds to one quarter of the real data. Figure 2 shows that the autocorrelation structure of the artificial series fits very well the autocorrelation function of the real series. The average first lag autocorrelation of our simulations is remarkably similar to that of the real data, especially for $\beta = 0.7$ (Table 3). Moreover, despite the standard deviation of the simulated series is much smaller than the standard deviation of the real series, our model proved able to reproduce an important feature of real macroeconomic data – namely, real consumption is less volatile than the real output.

[Figures 2a-d around here]

Figure 2: Box-plot of the autocorrelations of the 100 simulated series up to the 20th lag. The dashed line corresponds to the autocorrelation of the real series.

[11] We also tested both different values of ψ and rules in which wages are adjusted previously or concomitantly with the price level $\left(w_t = f\left(p_t\right)\right)$. Although in some cases the nominal wages lost their constancy, real wages did not display a remarkable different dynamics.

Table 3: Statistics of the cycle component

Real time series[1]	Standard deviation	First lag autocorrelation
Real output	1.6334	0.8464
Real consumption	1.2513	0.8180
Artificial series, $\beta = 0.7$[2]		
Real output	0.0220	0.8651
Real consumption	0.0215	0.8619
Artificial series, $\beta = 0.8$[2]		
Real output	0.0255	0.7428
Real consumption	0.0241	0.7124

(1): U.S. data retrieved from FRED (https://fred.stlouisfed.org/), codes GDPC1 (real output) and PCECC96 (real consumption), ranging from 1947-01-01 and 2017-04-01.
(2): Average of the 100 simulations.

3.2. Interest rate shock

We then run simulations including an interest rate shock, in the form of a temporary increase in i^B. The base interest rate is the instrument used by the central bank to implement its monetary policy. Thus, it is worth exploring how changes in this variable affect the real economy, as well as the price level and the financial fragility, which is measured by the NPL-to-aggregate credit ratio. As in the previous section, we are considering the average of 100 simulations.

We considered that, at period 1,000, the base interest rate varies positively by Δr and, after 50 periods, it turns back to its previous level. Note that the model replicates two kinds of tradeoffs: the inflation/output tradeoff and the inflation/financial stability tradeoff (Figure 3). Increases in the base interest rate reduce profits, thus affecting negatively consumption (through dividends) and output (through retained profits). Cascade effects take place, provoking further decreases in aggregate demand and production. In order to minimize profit losses, firms reduce markups to try to gain market share, which pushes prices down. Lower profits increase the occurrence of bankruptcies, thus worsening financial stability. An opposite mechanism takes place in case of a negative interest rate shock.

For large absolute values of Δr (equal to 25% of base interest rate), the macroeconomic effects of negative and positive shocks become asymmetric, being much stronger in the former case. In fact, they preclude the system from returning to its original path. This phenomenon does not seem to have much robust empirical support, but it can be logically and intuitively explained by characteristics of the model. After the transient period, eliminated firms have an average level of leverage which is smaller than that of the incumbent ones (Figure 1). With a positive interest rate shock, the resulting fall in aggregate demand forces leverage down. However, financial fragility increases, which attenuates such decrease in the leverage level and, consequently, in the output production: there will be more low-leveraged firms being eliminated and more high-leveraged firms being created, as entrant firms are random copies of incumbent ones. Meanwhile, a similar mechanism which can attenuate the change in leverage does not exist in the case of a negative interest rate shock.

[Figures 3a-d around here]

Figure 3: Aggregate real output (up-left), price level (up-right), NPL-to-total credit (down-left) and leverage (down-right) for various levels of Δr. Obs.: the variables are normalized to coincide at t=1,000.

4. Implementing monetary policy and prudential regulation

In this section, we explore how the system is affected by an active economic policy. We assume that the central bank has two targets: macroeconomic stability (hereafter, MS) and financial stability (FS). To achieve these objectives, the central bank relies on two instruments, respectively, the base interest rate i^B and the capital requirement ratio k.

The base interest rate is set according to a Taylor-type rule:

$$i_t^B = \chi \cdot i_{t-1}^B + (1-\chi)\cdot [r^* + \pi_{t-1} + \theta_1(\pi_{t-1} - \pi^T) + \theta_2 y_{t-1}^G + \theta_3(b_{t-1} - b^T)] \qquad (13).$$

In the equation above, r^* is the equilibrium real interest rate, π is the observed inflation, π^T is the inflation target, y^G is the output gap, b is the nominal credit-to-nominal output ratio, b^T is the potential level of b, χ is a smoothing parameter between 0 and 1 and θ_1, θ_2 and θ_3 are positive parameters.

The output gap is equal to $(Y_{t-1} - Y^T)/Y_{t-1}$, where Y^T is the potential output. Following Chiarella and Di Guilmi (2017), both Y^T and b^T are computed as a moving average on the past 5 periods. The base interest rate is never set below 0.1%.

By setting different values to parameters in equation (13), we explore the effects of three types of rules:

i. Traditional Taylor rule (TTR): $\chi = \theta_3 = 0$, $\theta_1 = \theta_2 = 0.5$. This establishes the rule proposed by Taylor (1993) in his seminal paper.

ii. Interest-rate smoothing (IRS): $\theta_3 = 0$, $\theta_1 = \theta_2 = 0.5$, $0 < \chi < 1$. In the actual conduct of monetary policy, central banks are frequently prone to adopt an inertial monetary policy, adjusting partially the policy interest rate. Clarida et al. (2000) estimate the smoothing parameter as ranging from 0.7 to 0.9. Some researchers claim that this can be an optimal behavior on the part of the central bank. Sack and Wieland (2000), for instance, consider that interest rate smoothing may be optimal due to three features of the environment in which monetary policy is conducted: forward-looking behavior by market participants, measurement error of key macroeconomic variables and uncertainty regarding structural parameters.

iii. "Leaning against the wind" interest rate (LAW): $\chi = 0$, $\theta_1 = \theta_2 = 0.5$, $\theta_3 > 0$. There is an intense discussion about whether monetary policy should react when an asset price bubble is identified or just after the bubble burst – the "lean versus clean" debate. The recent financial crisis has provided some arguments in favor of the first option (Canuto and Cavallari 2013). We explore this rule by using a variable associated with the potential creation of asset bubbles, viz. the credit expansion. Then we incorporate to the TTR a component which is sensible to the credit-to-output gap.

Regarding the capital requirement, we consider that it now incorporates a cyclical component k_t^C:

$$k_t = k^* + k_t^C \qquad (14).$$

As originally proposed by the Basel II accord (BCBS 2005), we establish $k^* = 0.08$, while k_t^C varies according to the credit-to-output gap:

$$k_t^C = \begin{cases} 0 & if \quad g_{t-1} \le L \\ 0.025 \cdot \dfrac{g_{t-1} - L}{H - L} & if \quad L < g_{t-1} < H \\ 0.025 & if \quad g_{t-1} \ge H \end{cases} \qquad (15),$$

where $g_t = b_t - b^T$ is the credit-to-output gap and *L* (*H*) is the lower (higher) threshold. In BCBS (2010), the suggested values for *L* and *H*, which we adopt here, are 0.02 and 0.10, respectively.

In the following analysis, this first rule is called the Basel II rule (BAS). Alternatively, we test a second capital requirement rule, which is adopted, for instance, in Agénor et al. (2013). Here, the capital requirement is $k_t = k^* + \theta^C g_{t-1}$, with $\theta^C > 0$. In the following analysis, we refer to this rule as the unbounded capital requirement rule (UNB).

Departing from UNB, we explore two more rules. Firstly, we analyze the effect of the capital requirement smoothing (CRS) rule, by setting $k_t = \chi \cdot k_{t-1} + (1-\chi) \cdot \left(k^* + \theta^C g_t\right)$. The latter is supported by the same rationale of IRS. Capital requirement smoothing is also a way to tackle the problem of pro-cyclicality: as banks capital requirements should be sensitive to changes in borrower default risk, credit falls during recessions and expands during economic booms, exacerbating both movements (Gordy and Howells 2006). Finally, the use of the deviation of the credit-to-output ratio from its trend in setting of capital requirement is criticized by many authors. Repullo and Saurina (2011) point out that it would exacerbate the pro-cyclicality of risk-sensitive bank capital regulation, as for many countries the credit-to-GDP gap is negatively correlated with GDP growth. Some studies suggest that the credit growth rate (e.g., Jordà et al 2010) is a better reference point. Therefore, we implement the credit growth capital requirement rule (CGR), according to which the capital requirement ratio is established according to $k_t = k^* + \theta^C \left(B_{t-1} - B^T\right)/ B_{t-1}$, where B^T is the potential credit, which is also estimated through the moving average on the last 5 periods.

As mentioned earlier, the central bank is concerned with macroeconomic stability and financial stability. We assume that the former depends negatively on the volatility of output and price, as measured by their coefficients of variation, while the latter is measured by the ratio NPL-to-total credit. In addition to such variability, we will also assess the average of price and output. This is supported by some studies (e.g., Svensson 1999; Ball et al 2005) according to which the optimal monetary policy should target the price level rather than inflation. Finally we will assess also the variability of the NPL-to-credit ratio. We explore how the behavior of these six variables (coefficient of variation of real output, coefficient of variation of prices, coefficient of variation of NPL-to-credit ratio, average price, average real output and average NPL-to-credit) is affected by each combination of monetary policy rule and capital requirement rule.

4.1. Results

Tables 4-5 show the results of simulations. For each combination, it was run 200 simulations of 1,000 periods each. The values shown in the cells correspond to the percentage difference between the average of the respective combination and that of the baseline case (fixed capital requirement and interest rate). For instance, in the simulations with the combination TTR and BAS, the average coefficient of variation of the real output is 47.5% smaller than that of the baseline case. As specified in the Appendix, we set $r^* = 0.02$, $\pi^T = 0$, $\chi = 0.5$ and $\theta^C = 0.5$. For the "leaning against the wind" rule, three values of θ_3 were tested: 0.1, 0.2 and 0.5. The first 400 periods were taken as transient phase and excluded from the calculations.

We can observe that all available instruments are individually effective. The interest rate rules, when applied alone, reduce their target variables (coefficient of variation of output and price). They are also effective in achieving financial stability, even in articulation with a fixed capital requirement. In the fixed interest rule case, the

BAS rule is the most successful one in reducing the average NPL-to-credit ratio, having also a significant effect on macroeconomic stability.

Table 4: Results of simulations – coefficient of variation of the variables

$k\backslash i^B$ Rule	FIR	TTR	IRS	LAW		
				θ_3=0.1	θ_3=0.2	θ_3=0.5
Coefficient of variation of the real output						
FCR	-	-38.2***	-28.6***	-39.7***	-37.6***	-19.9**
BAS	-46.4***	-47.5***	-43.7***	-45.8***	-35.1***	-15.7*
UNB	25.9*	-5.2	-19.5	-31.3***	-46.7***	-39.9***
CRS	1.9	-9.2	-19.9	-33.3***	-37.8***	-37.4***
CGR	-13.8	-43.7***	-47.4***	-35.6***	-40.0***	-33.3***
Coefficient of variation of prices						
FCR	-	-42.1***	-35.0**	-42.8***	-48.6***	-28.2*
BAS	-50.5***	-54.4***	-47.2***	-43.5***	-34.6*	-25.4
UNB	22.2	-15.3	-34.7**	-42.3***	-53.4***	-49.4***
CRS	-12.4	-23.3	-18.9	-46.1***	-50.9***	-43.2***
CGR	-23.1	-51.6***	-56.4***	-44.3***	-45.3***	-46.8***
Coefficient of variation of NPL-to-credit						
FCR	-	61.9**	88.7***	49.9**	30.8*	52.2**
BAS	49.4***	35.2*	54.5**	58.7**	54.2**	42.0*
UNB	-1.9	40.8***	52.2***	50.9**	58.5***	29.1**
CRS	-14.7	46.0***	60.4***	48.8***	42.7**	47.9*
CGR	6.2	46.4**	46.0***	36.3**	36.6**	21.7

Values correspond to the relative difference between the mean of the combination and that of the baseline case (FCR x FIR). The significance level is set according to the F-test of equality of means. (*): Significant at 10%. (**): Significant at 5%. (***): Significant at 1%. Interest rate rules: **FIR** – fixed interest rate; **TTR** – traditional Taylor rule; **IRS** – interest rate smoothing rule; **LAW** – leaning against the wind. Capital requirement rules: **FCR** – fixed capital requirement; **BAS** – Basel II rule; **UNB** – unbounded capital requirement rule; **CRS** – capital requirement smoothing rule; **CGR** – credit growth rule.

Table 5: Results of simulations – average of variables

$k \backslash i^B$ Rule	FIR	TTR	IRS	LAW		
				θ_3=0.1	θ_3=0.2	θ_3=0.5
Mean real output						
FCR	-	-52.9***	-55.7***	-50.7***	-50.2***	-41.7***
BAS	-54.2***	-53.7***	-57.2***	-51.1***	-50.9***	-43.5***
UNB	-3.3	-41.4***	-52.9***	-52.7***	-58.1***	-54.3***
CRS	-3.3	-43.2***	-52.3***	-51.4***	-58.4***	-57.3***
CGR	-23.9***	-53.6***	-58.7***	-56.0***	-55.5***	-48.3***
Mean price level						
FCR	-	-1.4***	-1.5***	-1.4***	-1.4***	-1.6***
BAS	-1.0***	-1.3***	-1.4***	-1.4***	-1.3***	-1.5***
UNB	-0.1	-0.8***	-1.1***	-1.2***	-1.5***	-1.4***
CRS	0.0	-0.9***	-1.3***	-1.3***	-1.7***	-1.7***
CGR	-0.3***	-1.4***	-1.5***	-1.4***	-1.3***	-1.3***
Mean NPL-to-credit						
FCR	-	-54.9***	-58.9***	-47.7***	-54.3***	-42.0***
BAS	-52.8***	-56.2***	-58.1***	-50.9***	-47.9***	-41.5***
UNB	-5.6**	-27.0***	-52.5***	-46.9***	-55.9***	-58.0***
CRS	-5.2*	-31.3***	-55.1***	-41.3***	-59.8***	-60.4***
CGR	-25.6***	-49.2***	-59.4***	-59.0***	-58.0***	-50.3***

Values correspond to the relative difference between the mean of the combination and that of the baseline case (FCR x FIR). The significance level is set according to the F-test of equality of means. (*): Significant at 10%. (**): Significant at 5%. (***): Significant at 1%. Interest rate rules: **FIR** – fixed interest rate; **TTR** – traditional Taylor rule; **IRS** – interest rate smoothing rule; **LAW** – leaning against the wind. Capital requirement rules: **FCR** – fixed capital requirement; **BAS** – Basel II rule; **UNB** – unbounded capital requirement rule; **CRS** – capital requirement smoothing rule; **CGR** – credit growth rule.

The effectiveness of the interest rate rules in accomplishing financial stability is due to the macro-financial linkage brought by the stock-flow consistency of our model. A worsening in the financial stability, for instance, with an increase in the NPL-to-credit ratio, will bring a decrease in the aggregate demand, as the net worth of the new firms is partially subtracted from households' resources. There will be a drop in the output and in the price level. Through the application of the interest rate rule, the interest rate will decrease. It reduces the credit cost and the probability of default, contributing for the recovery of the aggregate output as well as for the financial stability. This macro-financial linkage can also explain the absence of a trade-off regarding the pursuit of financial and macroeconomic stability. If some interest rate rule begot the best result regarding macroeconomic stability when combined with a given capital requirement rule, this combination is also the best alternative from the perspective of the financial stability. It is worth noting that, despite being effective in reducing the mean of the NPL-to-credit, interest rate rules increases its variability.

The performance of the capital requirement rules seems to be related to the aggressiveness of the interest rate rule. The "leaning against the wind" rule is sensitive to the credit-to-output gap, which is positively correlated to the output growth and inflation.[12] Hence the interest rate engendered by this rule reacts more aggressively to output and price movements, and this aggressiveness is increasing in the parameter θ_3. Under less aggressive interest rate rules (TTR, IRS and LAW for θ_3 equal to 0.1), the BAS performs similarly to the CGR rule and surpasses the other unbounded capital requirement rules (UNB and CRS), with respect to both financial and macroeconomic stability. This pattern changes as θ_3 increases. In fact, for θ_3 greater than 0.2, all the unbounded capital requirement rules bring better results than the BAS rule. This aspect will be further discussed in the next subsection.

The smoothing of interest rate proved better than the traditional Taylor rule with respect to financial stability when some capital requirement rule is applied. In fact, the decrease in the average NPL-to-credit ratio is higher in the former case. Woodford (1999, 2001) discusses the optimality of interest rate smoothing. In fact, it reduces the likelihood of reaching the zero nominal interest rate floor in a low interest rate environment and decreases the average size of distortions caused by high interest rates (Woodford 1999). Our model is backward-looking but, even in forward-looking models, in which current aggregate demand is affected by expected future interest rates, monetary policy inertia is optimal (Woodford 2001). This result goes in hand with the view of some studies that interest rate smoothing enhances financial stability. For instance, it is claimed that, as banks convert variable rate liabilities in fixed rate assets, inertia in interest rates is favorable to their solvency (Padoa-Schioppa 2002).

[12] In our simulations, the average correlation varies between 0.42 and 0.60, depending on the combination between the interest rate rule and the capital requirement rule.

The application of Taylor-type interest rate rules reduces significantly the level of price and output. The decrease in the average output is more expressive (above 30%) than that in the price level (between 1% and 2%). The threats brought by low inflation – in fact, in our simulations, the variation in the price level is virtually zero – have been discussed by policymakers (e.g., Constâncio 2014) as well as in academic studies. Low inflation tends to depress interest rates, leaving small room for cut it in case of output shortfalls (Arias et al 2016). Moreover, a stabilizing inflation process may engender a permanent effect on output through hysteresis. Assessing 122 recessions in advanced countries since the 1960's, Blanchard et al. (2015) report empirical findings which are suggestive of this phenomenon.

4.2. Sensitivity analysis

We can draw some relevant policy implications from our results. One of them is that interest rate smoothing proved to be beneficial to financial stability, for the reasons discussed above. Another one is that the performance of the interest rate and capital requirement rules is influenced by the rules of the other type they are combined with. It seems that, in order to guarantee both financial and macroeconomic stability, the aggressiveness of the interest rate should go in hand with the variability of the capital requirement. In fact, the BAS rule – under which the capital requirement varies between 8% and 10.5% – generates better results in articulation with less aggressive interest rate rules. Concomitantly, the unbounded capital requirement rules are more effective when the interest rate reacts more aggressively to output and price movements.

Inferring causality can be a very hard task in agent-based models. There are a lot of variables interacting in a nonlinear way so it is very difficult to identify which of them are responsible for a given observed phenomenon. Anyway, we can try to explain the above-mentioned fact in the following way. A variation in the interest rate causes a change in output and price. In order to bring stability to these variables, it is necessary a lagged variation in the capital requirement in the opposite direction with a similar intensity. For instance, if the interest rate increases sharply in one period, bringing a strong decrease in the output and price level, it is necessary a decrease in the capital requirement in the next period, in order to increase the supply of credit and pull the variables back to their trends. The narrower the window for the capital requirement variability, the lower the chance of such stabilizing effect to happen.

In order to go further on these insights, we performed a sensitivity analysis on some key parameters. First, the smoothing interest rate rule (IRS) was combined with three cyclical capital component rules (UNB, CRS and CGR), changing χ between 0 and 0.9 in increments of 0.1. For each value of the parameter 100 simulations were run and the average of the variables of interest (NPL-to-credit ratio, coefficient of variation of real output and coefficient of variation of price) was calculated. As done throughout this paper, the first 400 periods were excluded from the calculations.

Secondly, we implemented a new cyclical component rule that enabled us to test the impact of the variability of the capital requirement in the macroeconomic and financial stability. The cyclical component, expressed in (15), is now given by:

$$k_t^C = \begin{cases} -Z & if \quad g_{t-1} \leq L \\ Z \cdot \left(2\dfrac{g_{t-1} - L}{H - L} - 1 \right) & if \quad L < g_{t-1} < H \\ Z & if \quad g_{t-1} \geq H \end{cases} \qquad (16).$$

We varied Z between 0 and 0.05 in increments of 0.005 and set L and H equal to -0.1 and 0.1, respectively. When Z = 0, the cyclical component is equal to zero, corresponding to the FCR rule. The variability of the capital requirement increases along with Z. In its maximum dispersion (Z = 0.05), the capital requirement ranges between 3% and 13%. We combined this capital requirement rule with three interest rate rules: TTR, IRS and LAW (θ_3 = 0.2). As in the previous case, we run 100 simulations and calculated the average values of the variables after excluding the first 400 observations.

Figure 4 shows that, as expected, there is a decreasing relationship between the variables and the smoothing parameter χ – that is, an increase in the smoothing parameter of the interest rate contributes to a greater financial and macroeconomic stability. When the UNB rule is applied, the output and price volatility seems to be a concave function of χ. In all other cases, an almost linear curve fits better the simulated data. The fit is better when the financial stability variable (NPL-to-credit) is considered, which is shown by the greater R^2 (Table 6), except in the IRS case. Such result is expected, as in this case the financial stability stems essentially from the smoothed interest rate and relies less on *Z.*

Regarding the capital requirement volatility parameter Z (Figure 5), we can observe that, for small levels of capital requirement variation, the less aggressive interest rate rules (TTR and IRS) performs better than the LAW rule. Notwithstanding, as Z increases, the LAW rule brings the better results for macroeconomic and financial stability. Again, the R^2 is greater when the regression involves the NPL-to-credit ratio.

[Figures 4a-c around here]

Figure 4: Average NPL-to-credit (top), coefficient of variation of the real output (middle) and coefficient of variation of the price level (down) as functions of χ.

[Figures 5a-c around here]

Figure 5: Average NPL-to-credit (top), coefficient of variation of the real output (middle) and coefficient of variation of the price level (down) as functions of Z.

Table 6: R^2 of regressions

Rule/variable:	avg. NPL-to-credit	coeff. var. real output	coeff. var. price level
Z:			
IRS	0.4014	0.6845	0.5984
LAW	0.8620	0.5110	0.4810
TTR	0.9054	0.5717	0.4032
χ:			
CGR	0.8916	0.4116	0.4391
CRS	0.8639	0.6357	0.6698
UNB	0.8468	0.7114	0.7279

5. Concluding remarks

In this paper, we set forth an AB model well suited to performing macroeconomic policy analysis. The main purpose was to derive qualitative results with respect to the appropriate coordination between monetary policy and prudential regulation within this framework.

The model succeeds in replicating several important macroeconomic stylized facts (e.g., business cycles), as well as two tradeoffs that are relevant to the issues addressed here: the inflation/output tradeoff and the inflation/financial stability tradeoff. A positive interest rate shock pushes both output and prices down. Furthermore, the resulting decrease in firms' profits increases the likelihood of bankruptcies, thus threatening financial stability.

We also explored how different combinations of monetary policy and prudential regulation rules affect macroeconomic and financial stability. Some relevant policy implications could be drawn from this analysis. First, the efficacy of a given capital requirement rule or interest rate rule depends on the specification of the rule of the other type it is combined with. Specifically, it was found that less aggressive interest rate rules perform better when capital requirement varies less. A possible explanation is that, in order to counterbalance the output and price variation brought by high interest rate reactiveness, the capital requirement should vary lagged in time with a similar intensity. Second, interest rate smoothing is more effective than the other interest rate rules assessed, as it outperforms those other rules with respect to financial stability and macroeconomic stability. This optimality of the interest rate smoothing find support in other studies (e.g., Woodford 1999, 2001). Third, there is no tradeoff between financial and macroeconomic stability with respect to the variability of the capital requirement, as well as the smoothing interest rate parameter. There is a negative relationship between the NPL-to-credit ratio and output and price volatility and the smoothing parameter. Moreover, the relationship between macroeconomic stability and the volatility of the capital requirement is qualitatively similar to the relationship between this parameter and financial stability, though they differ depending on the interest rate rule considered. Finally, our results reinforce the cautionary finding of other studies regarding how output can be ravaged by a low inflation targeting.

Needless to say, all these qualitative results should be taken with caution. Agent-based models suffer from over-parametrization and their results are very sensitive to parameters and initial conditions. However, similar caution applies to other types of modeling approaches addressing the same issues. Furthermore, the model set forth in this paper is characterized by an aggregate consistency between stocks and flows, a coherence of assumptions and the replication of stylized facts. Therefore, agent-based models along the lines of the one developed in this paper can be an important tool in the assessment of economic policies, acting complementarily to existing ones.

References

Agénor P-R, Alper K, Silva LAP (2013) Capital Regulation, Monetary Policy, and Financial Stability. International Journal of Central Banking 9 (3): 193-238

Arias JE, Erceg C, Trabandt M (2016) The Macroeconomic Risks of Undesirably Low Inflation. European Economic Review 88: 88-107

Assenza T, Delli Gatti D, Grazzini J (2015) Emergent dynamics of a macroeconomic agent based model with capital and credit. Journal of Economic Dynamics and Control 50: 5-28

Ball L, Mankiw NG, Reis R (2005) Monetary policy for inattentive economies. Journal of Monetary Economics 52 (4): 703-725

Barnea E, Landskroner Y, Sokoler M (2015) Monetary policy and financial stability in a banking economy: Transmission mechanism and policy tradeoffs. Journal of Financial Stability, 18 (In Progress): 78-90

Basel Committee on Banking Supervision (BCBS) (2005) International convergence of capital measurement and capital standards: a revised framework. Bank of International Settlements, Basel, Switzerland

____________ (2012) Models and tools for macroprudential analysis. BIS Working Paper No 21

Beau D, Clerc L, Mojon B (2012) Macro-prudential Policy and the Conduct of Monetary Policy. Bank of France Working Paper No. 390

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

Blanchard O, Cerutti E, Summers L (2015) Inflation and Activity: Two Explorations and Their Monetary Policy Implications. NBER Working Paper 21726

Bookstaber R (2012) Using Agent-Based Models for Analyzing Threats to Financial Stability. Office of Financial Research Working Paper No 0003

Canuto O, Cavallari M (2013) Monetary Policy and Macro Prudential Regulation: Whither Emerging Markets. In: Canuto O, Gosh S R (eds) Dealing with the Challenges of Macro Financial Linkages in Emerging Markets. The World Bank, Washington D. C.

Chiarella C, Di Guilmi C (2017). Monetary Policy and Debt Deflation: Some Computational Experiments. Macroeconomic Dynamics 21(1): 214-242

Cincotti S, Raberto M, Teglio A (2011) The EURACE macroeconomic model and simulator. 16th IEA World Congress

Cincotti S, Raberto M, Teglio A (2012) Macroprudential Policies in an Agent-Based Artificial Economy. Revue de l'OFCE 124 (5): 205-234

Clarida R, Gali J, Gertler M (2000) Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory. Quarterly Journal of Economics 115: 147-180

Constâncio V (2014) Recent Challenges to Monetary Policy in the Euro Area. Speech 44 by Vitor Constâncio, Vice-President of the ECB, at the Athens Symposium on Banking Union, Monetary Policy and Economic Growth, Athens, 19 June 2014

Delli Gatti D, Desiderio S (2015) Monetary policy experiments in an agent-based model with financial frictions. Journal of Economic Interaction and Coordination 10(2): 265-286

Delli Gatti D, Di Guilmi C, Gallegati M, Giulioni G (2007) Financial Fragility, Industrial Dynamics and Business Fluctuations in an Agent Based Model. Macroeconomic Dynamics 11 (S1): 62-79

Delli Gatti D, Gallegati M, Greenwald B, Russo A, Stiglitz JE (2009) Business fluctuations and bankruptcy avalanches in an evolving network economy. Journal of Economic Interaction and Coordination 4(2): 195-212

Delli Gatti D, Gallegati M, Greenwald B, Russo A, Stiglitz JE (2010) The financial accelerator in an evolving credit network. Journal of Economic Dynamics and Control 34(9): 1627-1650

Dosi G, Fagiolo G, Napoletano M, Roventini, A (2013) Income Distribution, Credit and Fiscal Policies in an Agent-Based Keynesian Model. Journal of Economic Dynamics and Control 37 (8): 1598-1625

dos Santos CH, Zezza G (2008) A Simplified, ‘Benchmark’, Stock-Flow Consistent Post-Keynesian Growth Model. Metroeconomica 59 (3): 441-478

Fabiani S, Druant M, Hernando I, Kwapil C, Landau B, Loupias C, Martins F, Mathä T, Sabbatini R, Stahl H, Stokman A (2006) What Firms' Surveys Tell Us about Price-Setting Behavior in the Euro Area. International Journal of Central Banking 2 (3): 3-47

Fagiolo G, Roventini A (2012) Macroeconomic Policy in DSGE and Agent-Based Models. Revue de l'OFCE 124 (5): 67-116

Flannery MJ, Rangan KP (2006) Partial adjustment toward target capital structures. Journal of Financial Economics 79(3): 469-506

Frank MZ, Goyal VK (2008) Tradeoff and Pecking Order Theories of Debt. In: Eckbo BE (ed) The Handbook of Empirical Corporate Finance. Elsevier, Amsterdam

_________________ (2015) The Profits-Leverage Puzzle Revisited. Review of Finance 19 (4): 1415–1453

Gallegati M, Kirman A (2012) Reconstructing Economics: Agent Based Models and Complexity. Complexity Economics 1: 5-31

Godley W, Lavoie M. (2007) Monetary Economics: An integrated Approach to Credit, Money, Income, Production and Wealth. Palgrave Macmillan, New York

Goodhart CAE, Kashyap AK, Tsomocos DP, Vardoulakis AP (2013) An Integrated Framework for Analyzing Multiple Financial Regulations. International Journal of Central Banking 9 (S1): 109–143

Gordy MB, Howells B (2006) Procyclicality in Basel II: Can we Treat the Disease without Killing the Patient? Journal of Financial Intermediation 15: 396-418

International Monetary Fund (IMF) (2013) The interaction of monetary and macroprudential policies. January

Jensen MC, Meckling WH (1976) Theory of the Firm: Managerial Behavior, Agency Costs, and Ownership Structure. Journal of Financial Economics 3: 305-360

Jordà O, Schularick M, Taylor AM (2010) Financial Crises, Credit Booms, and External Imbalances: 140 Years of Lessons" NBER Working Paper No. 16567

Krug S (2015) The interaction between monetary policy and macroprudential policy: Should central banks "lean against the wind" to foster macro-financial stability? Economics Working Paper No 2015-08, Christian-Albrechts-Universitat zu Kiel

Krug S, Lengnick M, Wohltmann HW (2015) The impact of Basel III on financial (in) stability: An agent-based credit network approach. Quantitative Finance 15 (12): 1917–1932

Krugman P (1996) The Self-Organizing Economy. Blackwell, Oxford

Lambertini L, Mendicino C, Punzi MT (2013) Leaning against boom–bust cycles in credit and housing prices. Journal of Economic Dynamics and Control 37 (8): 1500–1522

Mandel A, Jaeger C, Fuerst S, Lass W, Lincke D, Meissner F, Pablo-Marti F, Wolf S (2010) Agent-Based Dynamics in Disaggregated Growth Models. Working Paper 201077, CES

Myers SC (1977) Determinants of corporate borrowing. Journal of Financial Economics 5(2): 147-175

Neuberger D, Rissi R (2012) Macroprudential banking regulation: Does one size fit all? Thünen-Series of Applied Economic Theory, University of Rostock, Institute of Economics

Padoa-Schioppa T (2002) Central banks and financial stability: exploring a land in between. Second ECB Central Banking Conference The transformation of the European financial system, Frankfurt am Main

Palley T (2016) Inequality, the financial crisis and stagnation: competing stories and why they matter. Real-World Economics Review 74: 1-19

Popoyan L, Napoletano M, Roventini A (2017) Taming macroeconomic instability: Monetary and macro-prudential policy interactions in an agent-based model. Journal of Economic Behavior & Organization 134: 117-140

Raberto M, Teglio A, Cincotti S (2008) Integrating Real and Financial Markets in an Agent-Based Economic Model: An Application to Monetary Policy Design. Computational Economics 32: 147–162

Repullo R, Saurina J (2011) The Countercyclical Capital Buffer of Basel III: A Critical Assessment. CEPR Discussion Paper 8304

Riccetti L, Russo A, Gallegati M (2013a) Financial regulation in an agent-based macroeconomic model. Working Paper SSRN: http://dx.doi.org/10.2139/ssrn.2345904

Riccetti L, Russo A, Gallegati M (2013b) Leveraged network-based financial accelerator. Journal of Economic Dynamics and Control 37 (8): 1626-40

Riccetti L, Russo A, Gallegati M (2013c) Unemployment Benefits and Financial Factors in an Agent Based Macroeconomic Model. Economics Discussion Papers, No 2013-9, Kiel Institute for the World Economy

Riccetti L, Russo A, Gallegati M (2015) An agent based decentralized matching macroeconomic model. Journal of Economic Interaction and Coordination 10 (2): 305-332

Rotemberg J (2008) Behavioral Aspects of Price Setting, and Their Policy Implications. NBER Working Paper 13754

Sack B, Wieland V (2000) Interest-rate smoothing and optimal monetary policy: a review of recent empirical evidence. Journal of Economic and Business 52: 205-228

Setterfield M (2012) Real Sector Imbalances and the Great Recession. In: Herr H et al (eds) From Crisis to Growth?: The Challenge of Debt and Imbalances. Metropolis-Verlag, Marburg

Skott P (2013) Increasing Inequality and Financial Instability. Review of Radical Political Economics 45 (4): 478-488

Svensson LEO (1999) Price-Level Targeting versus Inflation Targeting: A Free Lunch? Journal of Money, Credit and Banking 31 (3): 277-295

Taylor JB (1993) Discretion versus policy rules in practice. Carnegie-Rochester Conference Series on Public Policy 39: 195-214

Teglio A, Raberto M, Cincotti S (2012) The impact of banks' capital adequacy regulation on the economic system: an agent-based approach. Advances in Complex Systems 15 (S2)

van der Hoog S (2015) The limits to credit growth: Mitigation policies and macroprudential regulations to foster macrofinancial stability and sustainable debt. Bielefeld Working Papers in Economics and Management No. 08-2015

Woodford M (1999) Optimal monetary policy inertia. CFS Working Paper No 1999/09

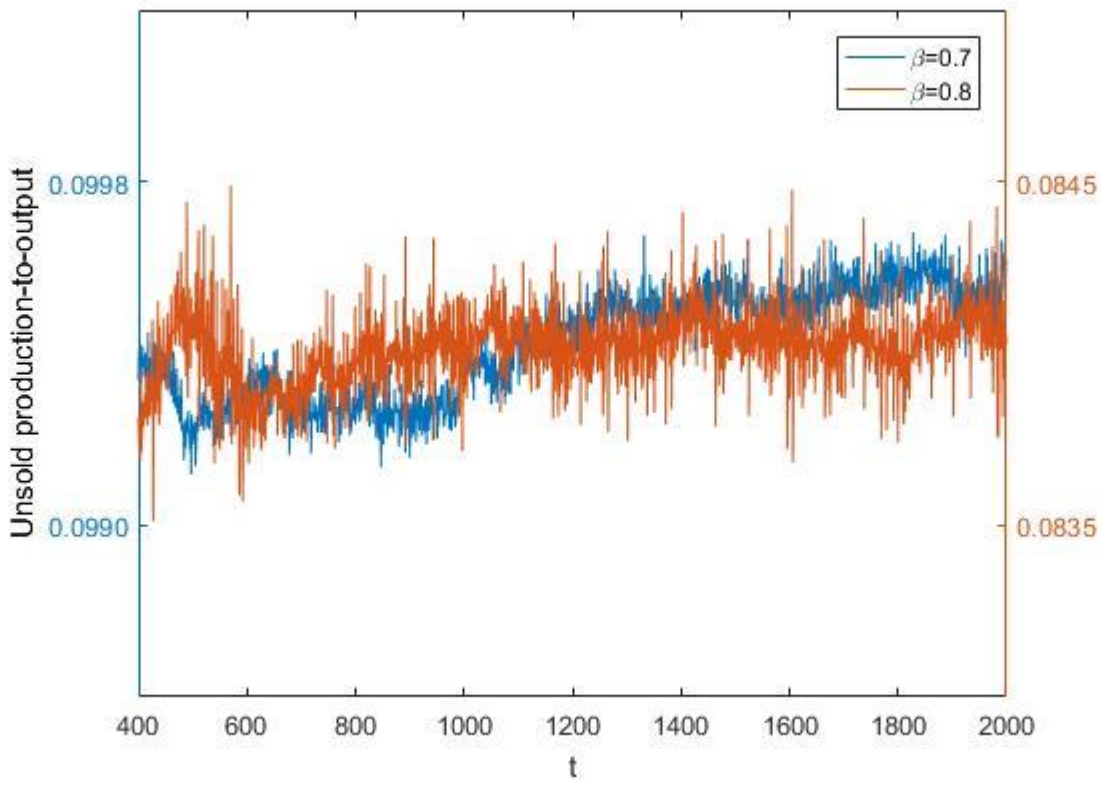
____________ (2001) The Taylor Rule and Optimal Monetary Policy. American Economic Review 91 (2): 232–237

Appendix: Parameters and initial conditions

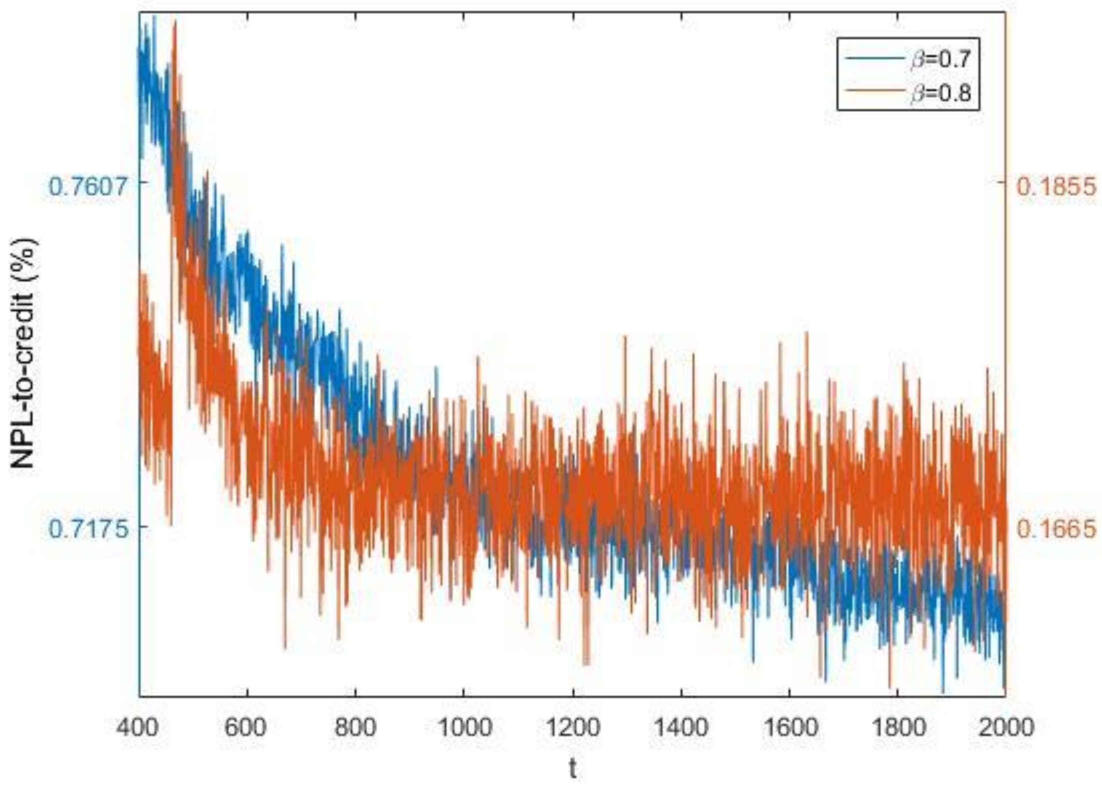
Number of Monte Carlo simulations		100[(1)]
Symbol	**Meaning**	**Value**
Parameters		
N	Number of firms	500
α	Production parameter (see equation 1)	3
β	Production parameter (see equation 1)	0.7
t_D	Duration of debts (in periods)	10
η	Labor productivity	1
ψ	Real wage lower limit parameter (see equation 3)	0.95
δ	Fraction of profits distributed as dividends	0.25
τ	Tax rate	0.25
φ	Markup sensitivity to a change in market share (see equation 6)	0.2
λ	Leverage sensitivity to a change in demand (see equation 10)	1
i^B	Base interest rate	0.02
k	Capital requirement ratio	0.08
γ	Risk premium parameter (see equation 11)	0.02
Initial conditions		
$NW_{i,0}$ (2)	Firms' initial net worth	$NW_{i,0} \sim N(10,2)$
$\mu_{i,0}$ (3)	Firms' initial markup	$\mu_{i,0} \sim N(0.15,0.03)$
w_0	Initial nominal wage	1
$l^*_{i,0}$	Firms' initial leverage target	$l^*_{i,0} \sim U(0.01,3)$
$s_{i,0}$	Firms' initial market share	$NW_{i,0} / \sum NW_{i,0}$
NW^B_o	Banking system's initial net worth	$2k \sum NW_{i,0}$
Γ_0	Government initial surplus	10,000
Policy rules parameters		
$r*$	Equilibrium real interest rate	0.02
π^T	Inflation target	0
χ	Smoothing parameter of the interest rate rule	0.5[(4)]
θ_1	Sensitivity of the interest rate to the inflation	0.5
θ_2	Sensitivity of the interest rate to the output gap	0.5
θ_3	Sensitivity of the interest rate to the credit-to-output gap	[0.1, 0.2, 0.5][(5)]
θ^C	Sensitivity of the capital requirement to the credit-to-output gap (UNB and CRS rules) or to the credit gap (CGR rule)	0.5

(1): For the policy analysis in Section 4.1: 200 simulations.
(2): Initial net worth is never set below 1.
(3): Initial markup is never set below 1%.
(4): Out of the IRS rule: zero.
(5): Out of the LAW rule: zero.

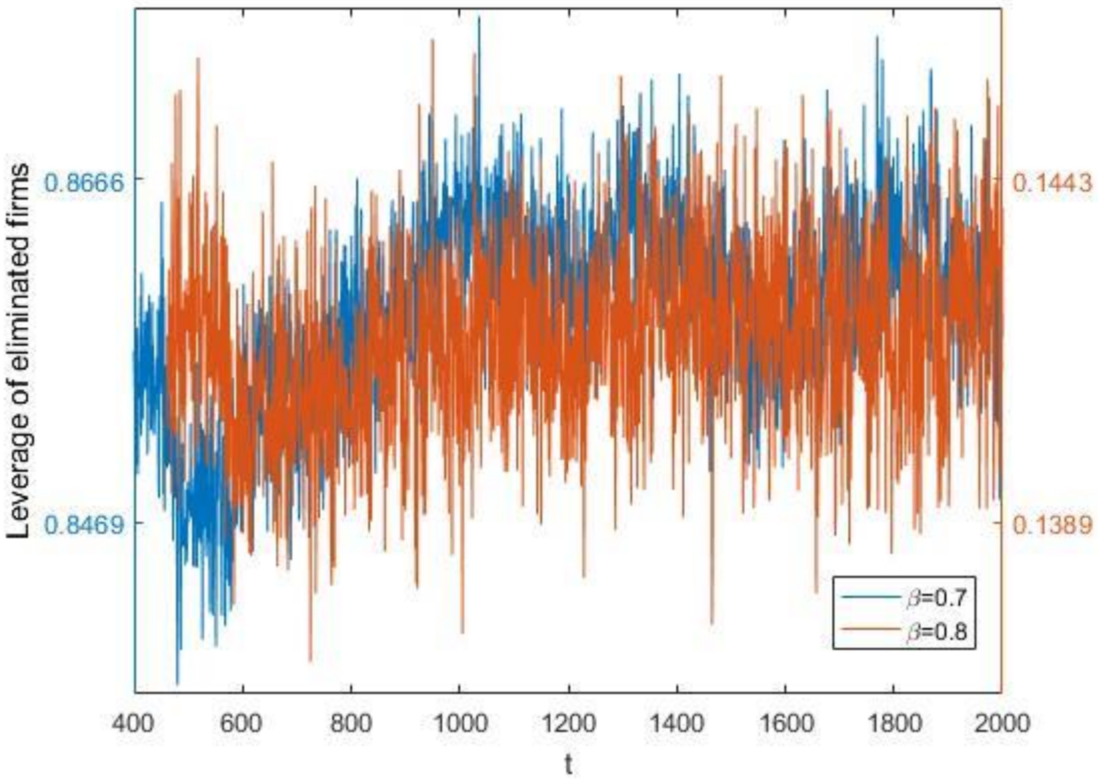
Figures 1a-h

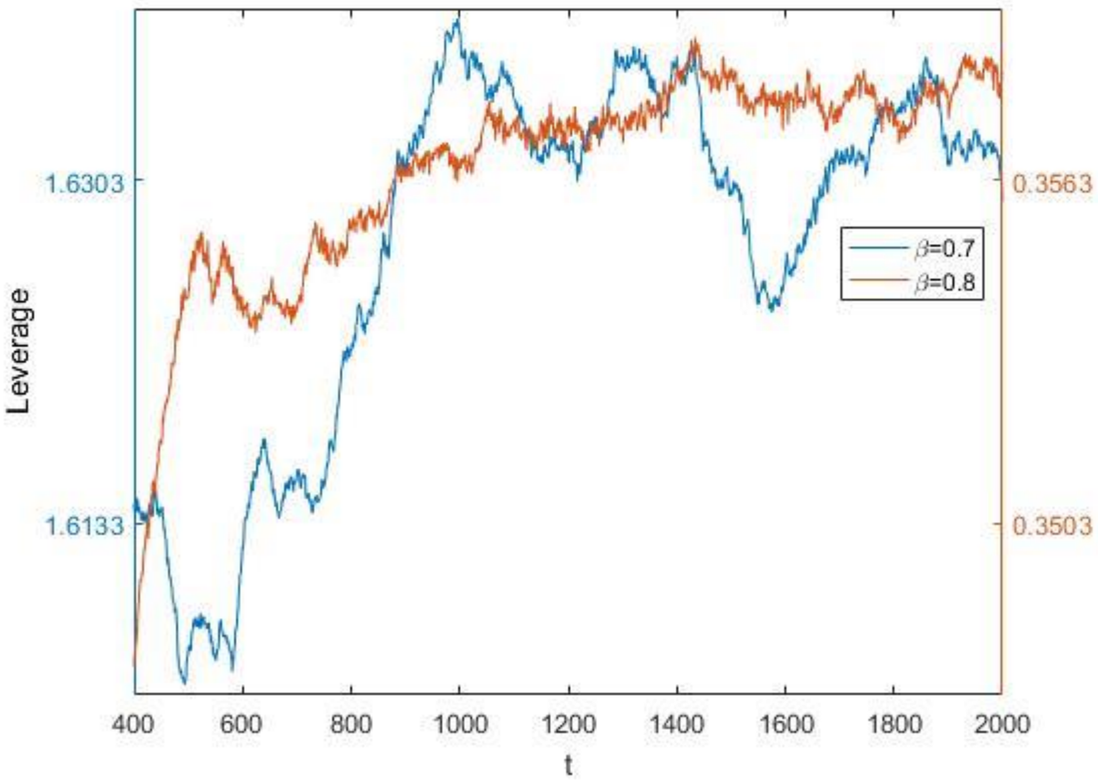


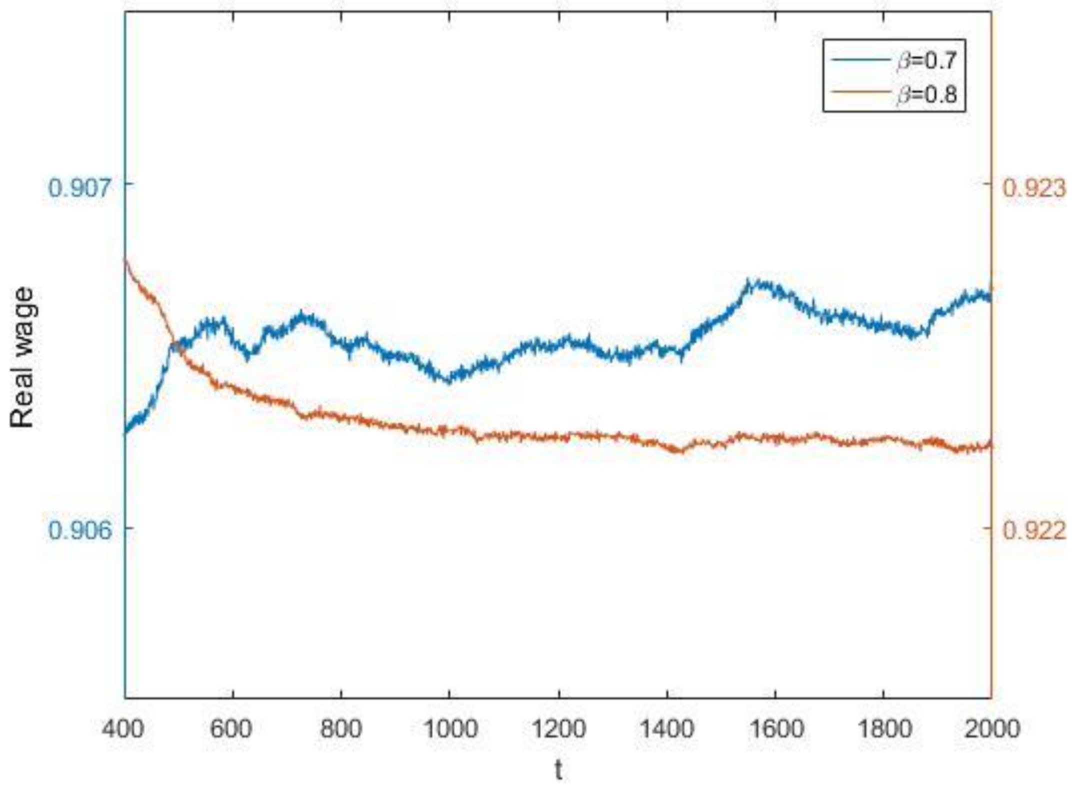
β=0.7
β=0.8
Unsold production-to-output
0.0998
0.0990
0.0845
0.0835
400
600
800
1000
1200
1400
1600
1800
2000
t



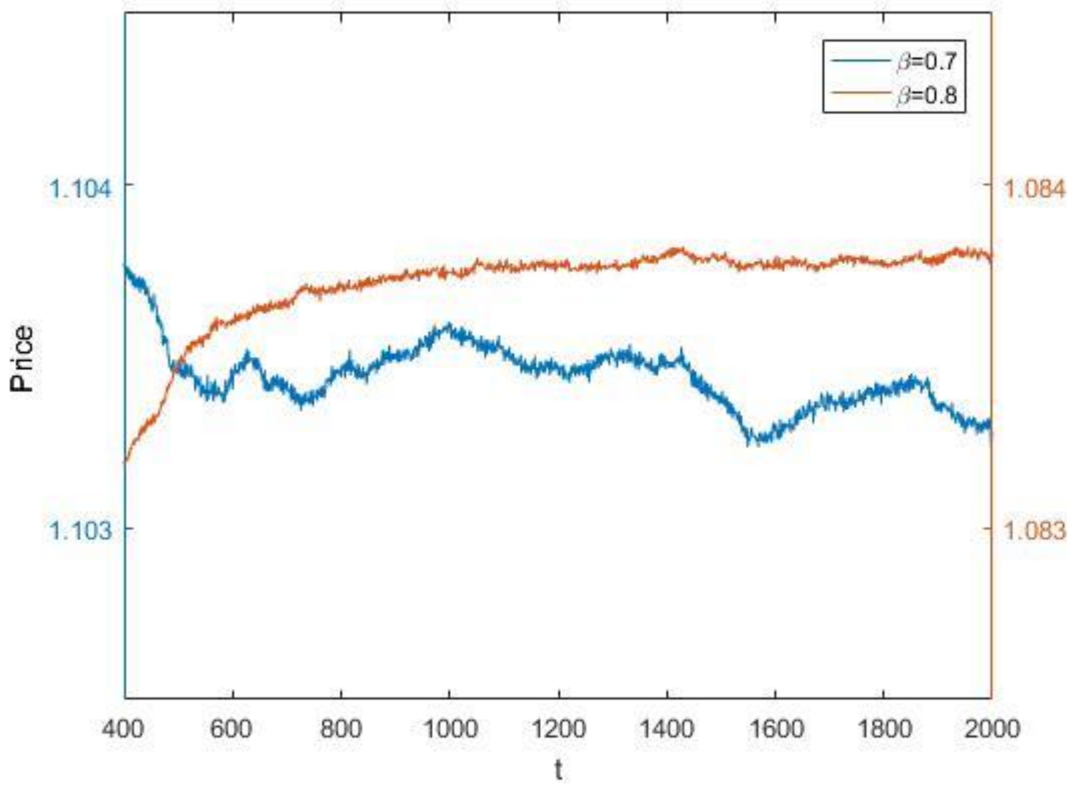
β=0.7
β=0.8
NPL-to-credit (%)
0.7607
0.7175
0.1855
0.1665
400
600
800
1000
1200
1400
1600
1800
2000
t


Leverage of eliminated firms
0.8666
0.8469
0.1443
0.1389
β=0.7
β=0.8
400
600
800
1000
1200
1400
1600
1800
2000
t

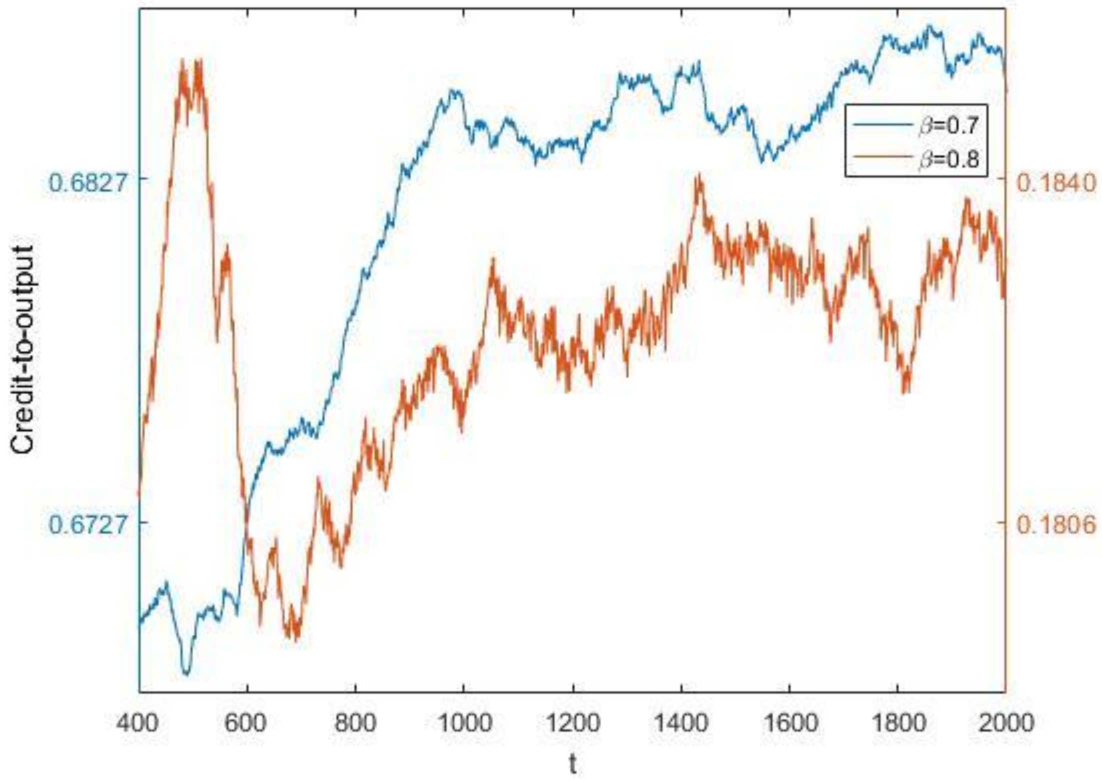

Leverage
1.6303
1.6133
0.3563
0.3503
β=0.7
β=0.8
400
600
800
1000
1200
1400
1600
1800
2000
t



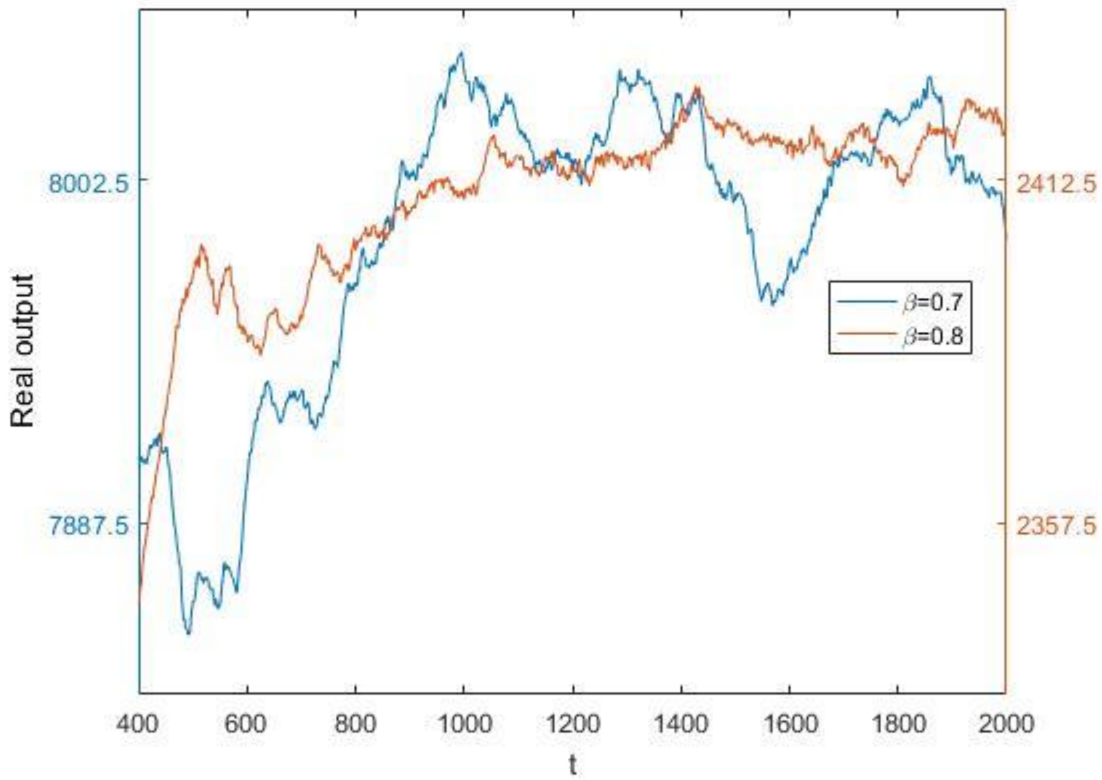
β=0.7
β=0.8
0.907
0.906
0.923
0.922
Real wage
400
600
800
1000
1200
1400
1600
1800
2000
t



β=0.7
β=0.8
1.104
1.103
1.084
1.083
Price
400
600
800
1000
1200
1400
1600
1800
2000
t

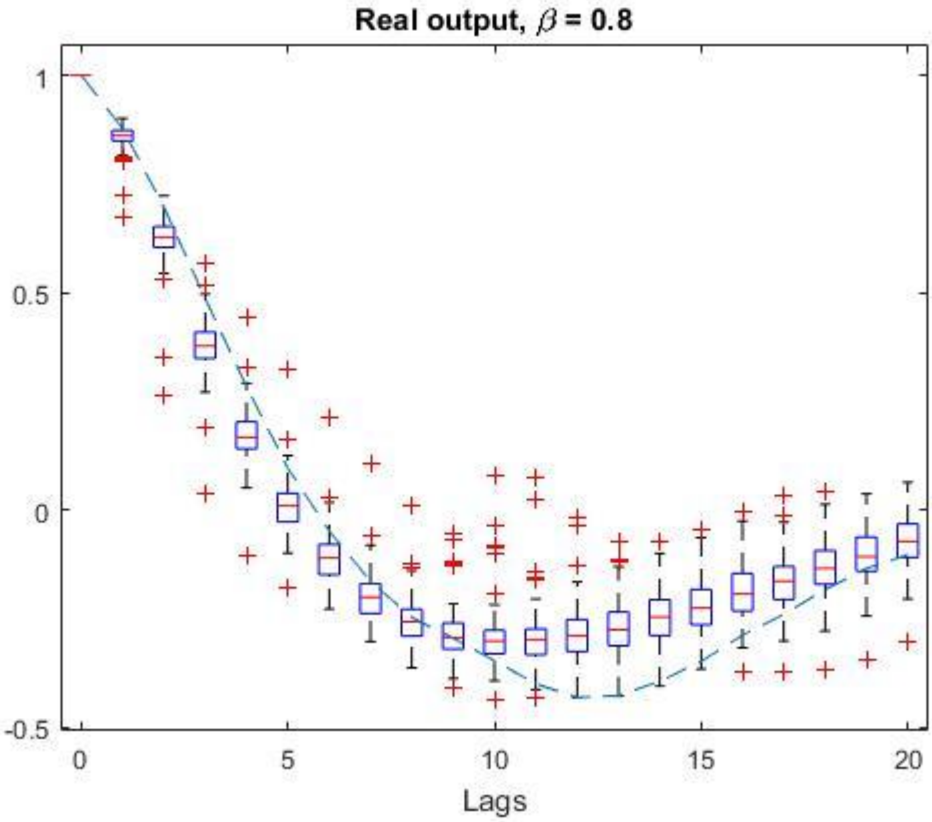


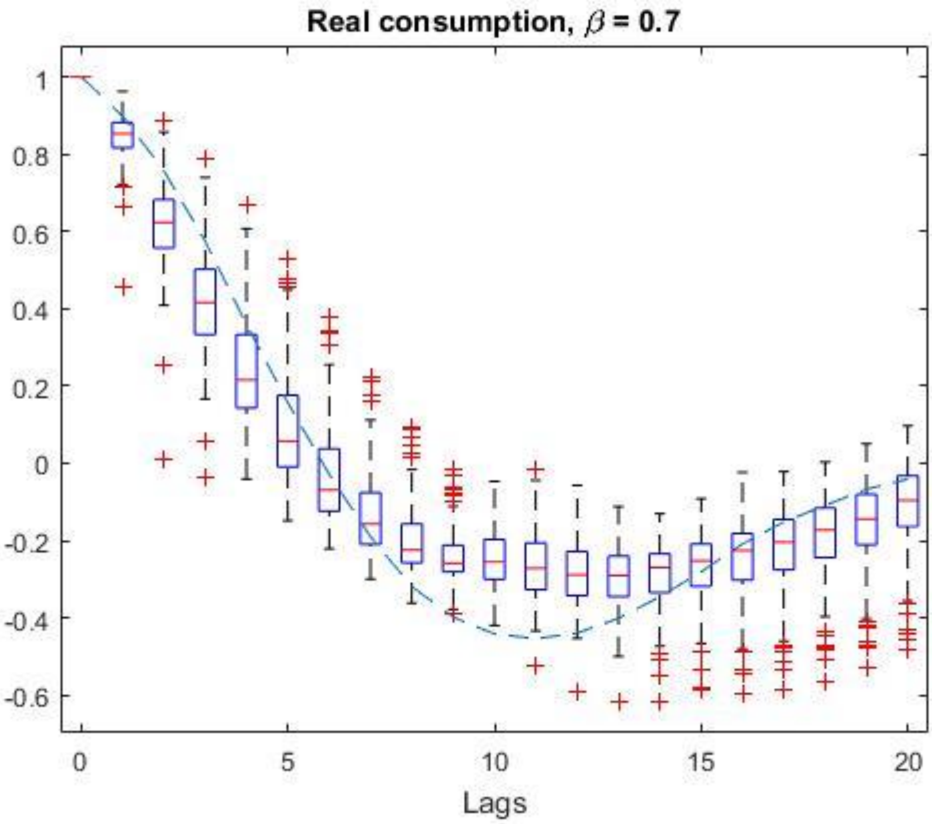
Credit-to-output
0.6827
0.6727
0.1840
0.1806
β=0.7
β=0.8
400
600
800
1000
1200
1400
1600
1800
2000
t

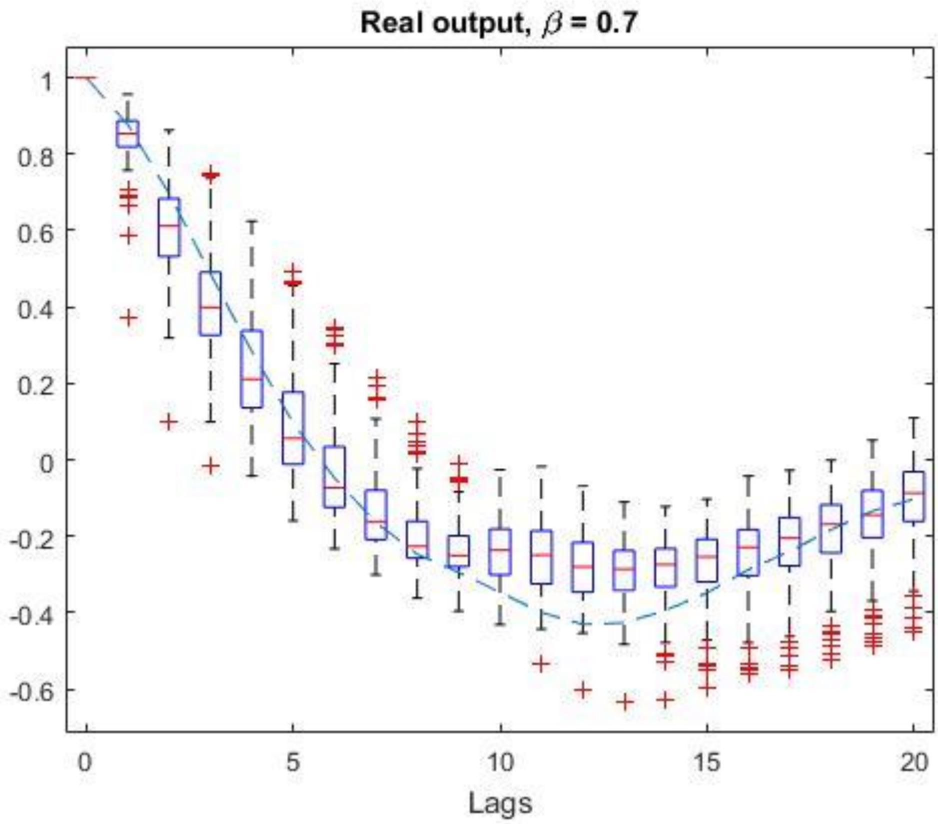


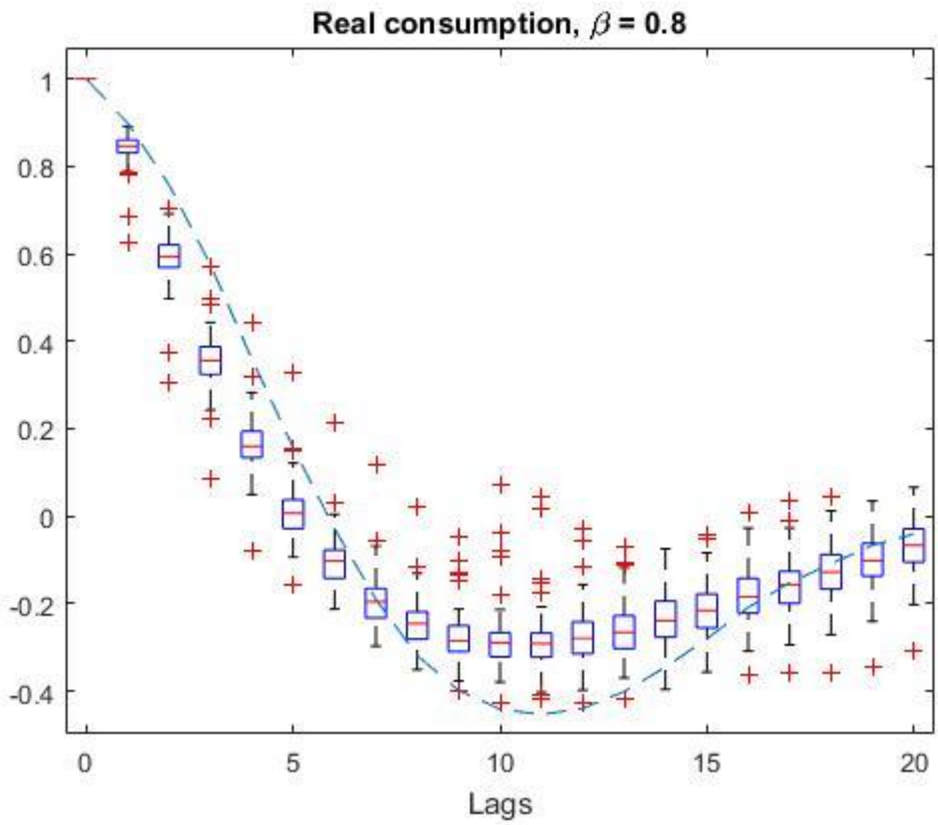
Real output
8002.5
7887.5
2412.5
2357.5
β=0.7
β=0.8
400
600
800
1000
1200
1400
1600
1800
2000
t

Figures 2a-d

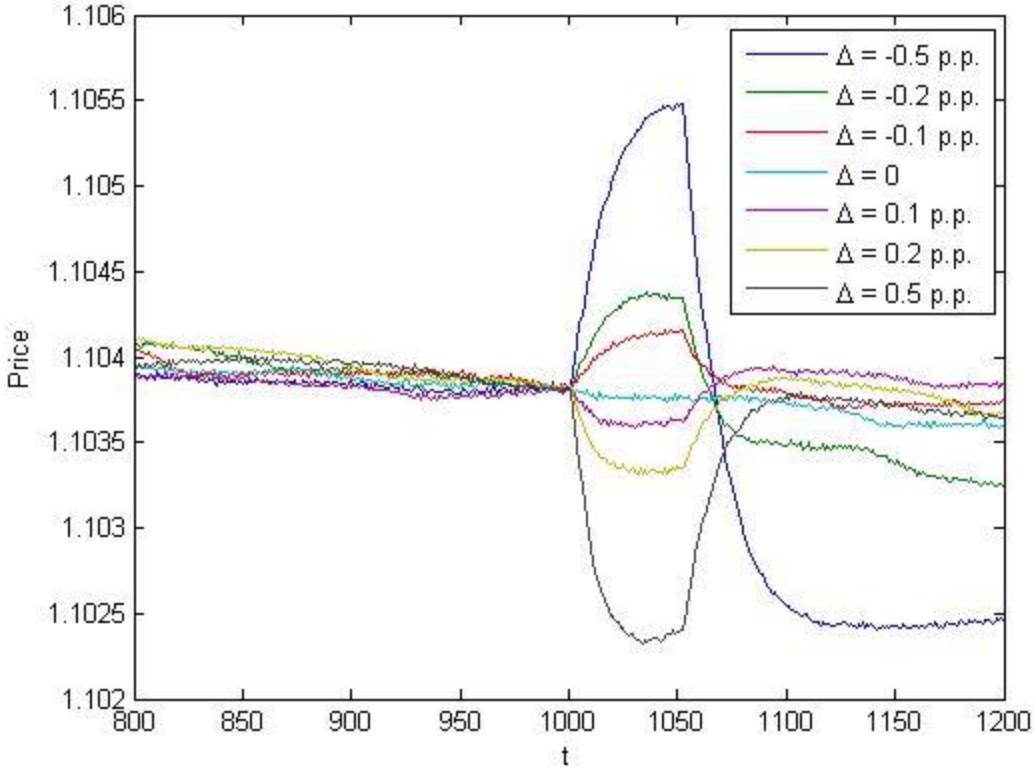

Real output, β = 0.8
1
0.5
0
-0.5
0
5
10
15
20
Lags

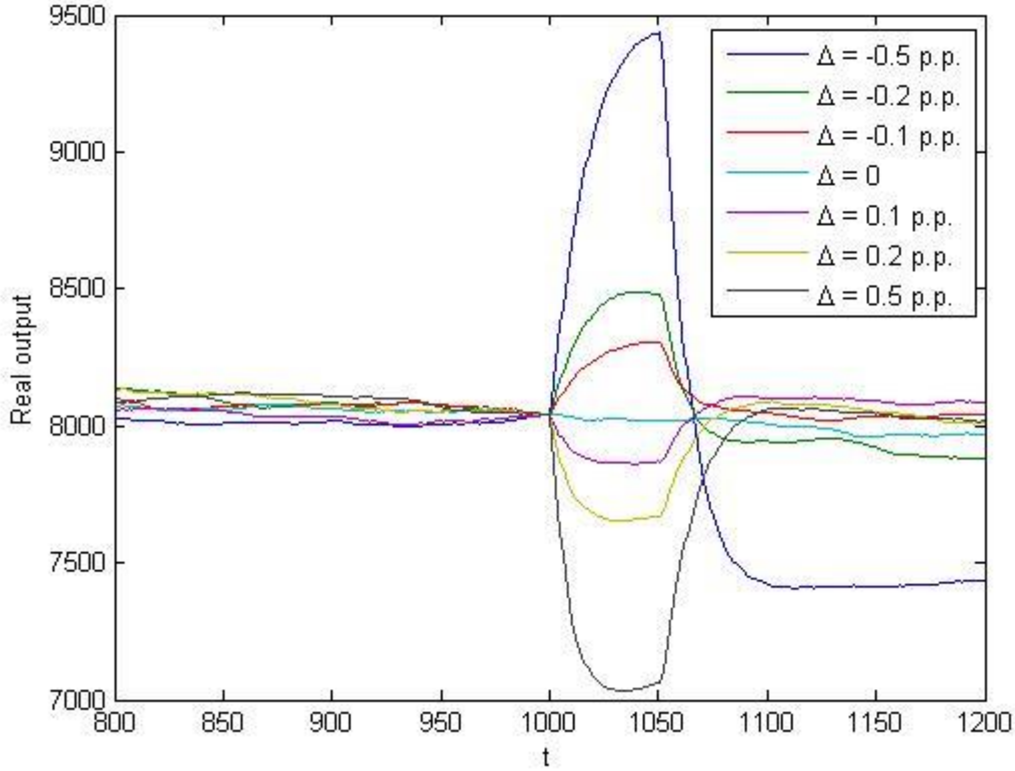

Real consumption, β = 0.7
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
5
10
15
20
Lags

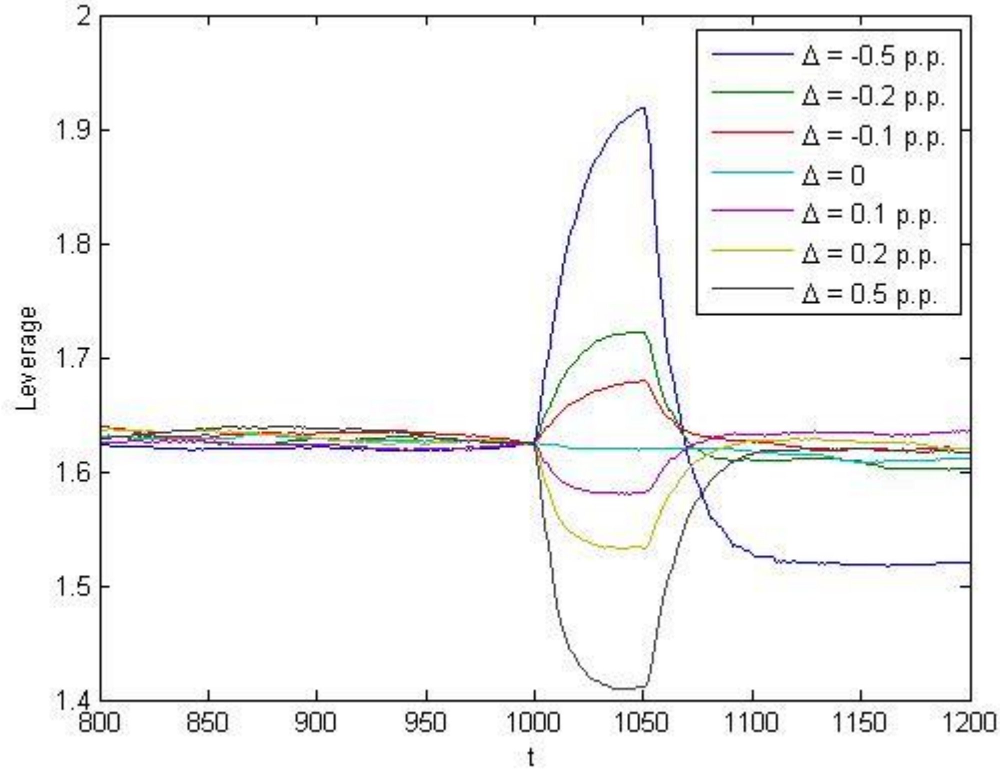

Real output, β = 0.7
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
5
10
15
20
Lags

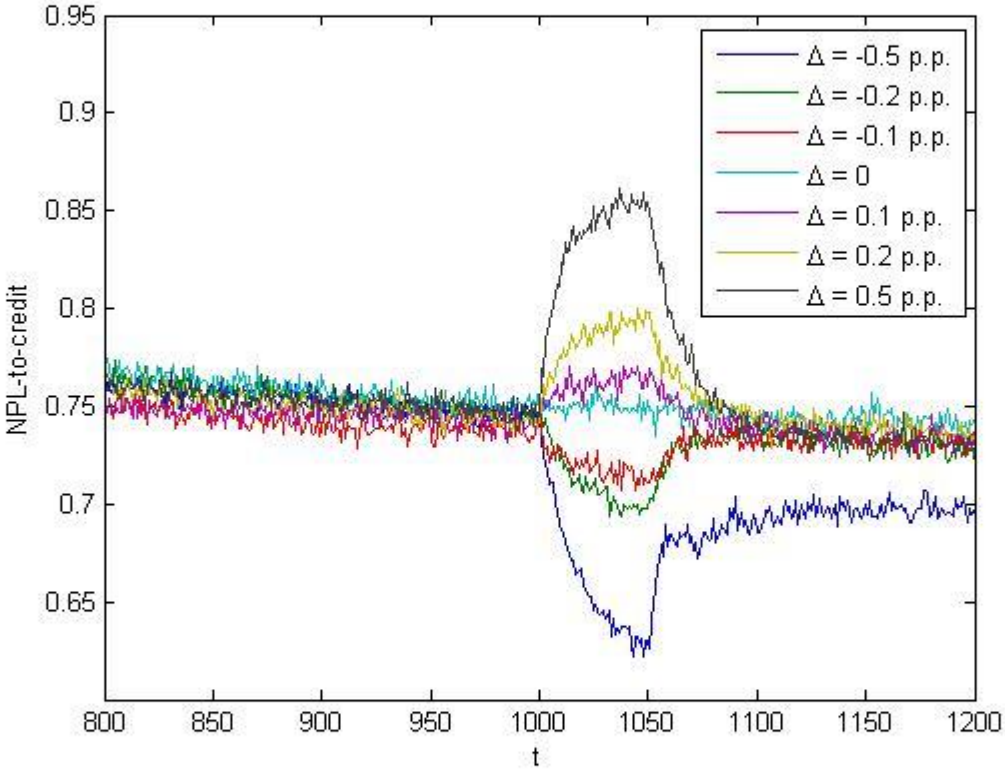

Real consumption, β = 0.8
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
Lags

Figures 3a-d

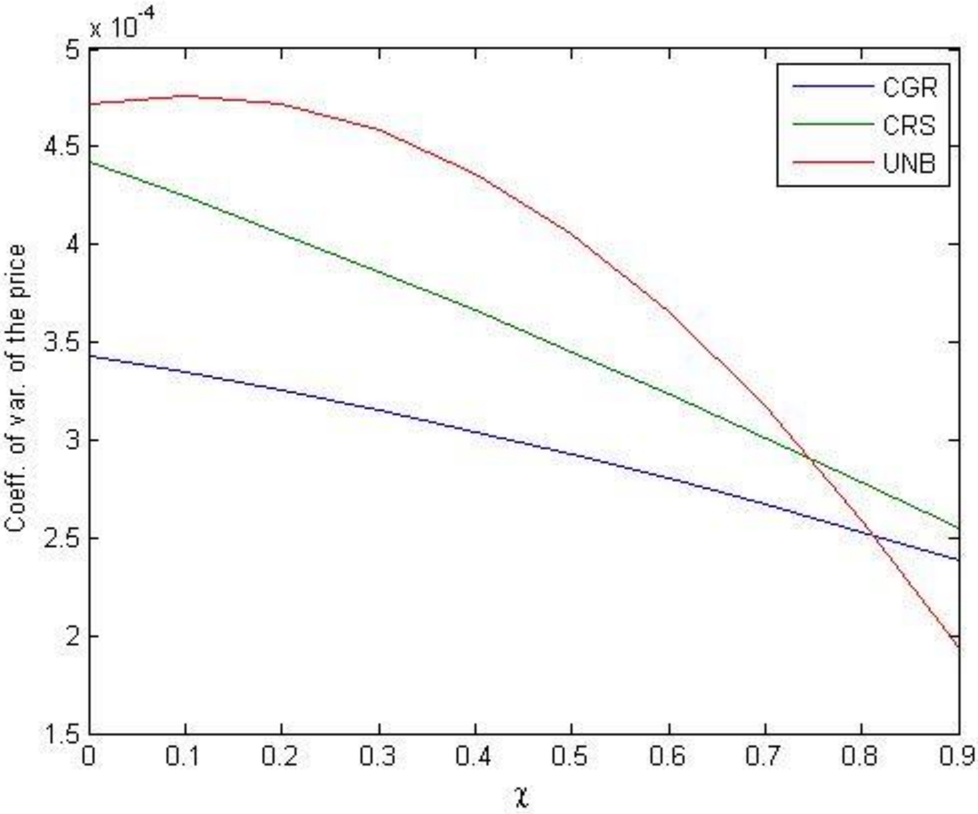

Price
t
Δ = -0.5 p.p.
Δ = -0.2 p.p.
Δ = -0.1 p.p.
Δ = 0
Δ = 0.1 p.p.
Δ = 0.2 p.p.
Δ = 0.5 p.p.
1.102
1.1025
1.103
1.1035
1.104
1.1045
1.105
1.1055
1.106
800
850
900
950
1000
1050
1100
1150
1200

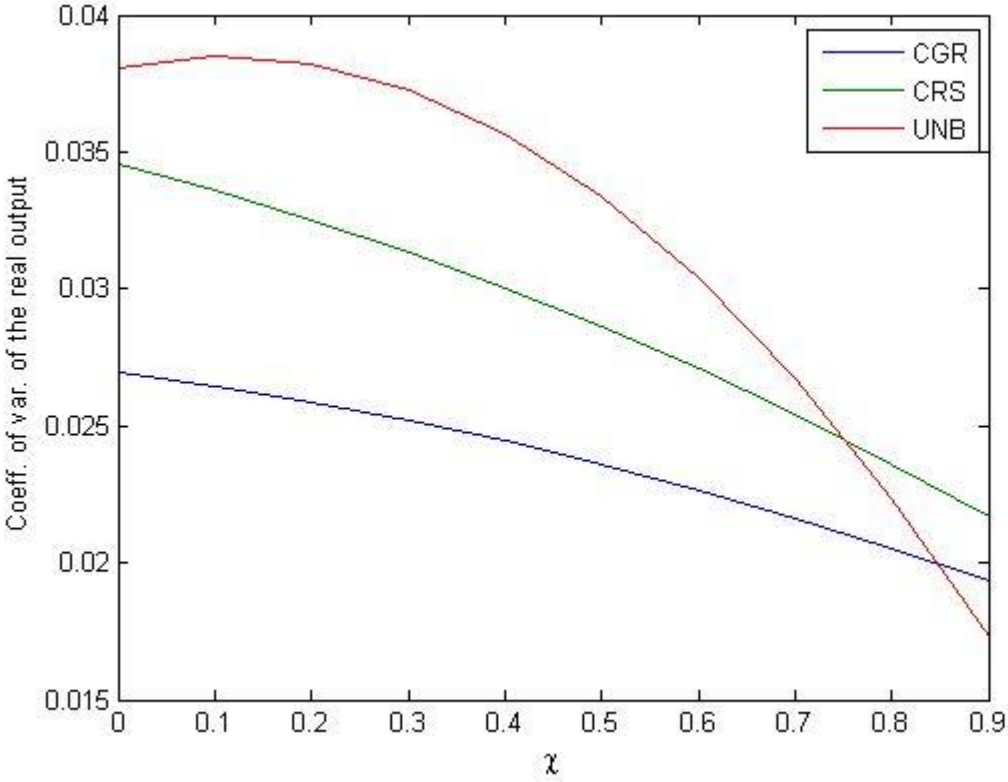

Real output
t
Δ = -0.5 p.p.
Δ = -0.2 p.p.
Δ = -0.1 p.p.
Δ = 0
Δ = 0.1 p.p.
Δ = 0.2 p.p.
Δ = 0.5 p.p.
7000
7500
8000
8500
9000
9500
800
850
900
950
1000
1050
1100
1150
1200

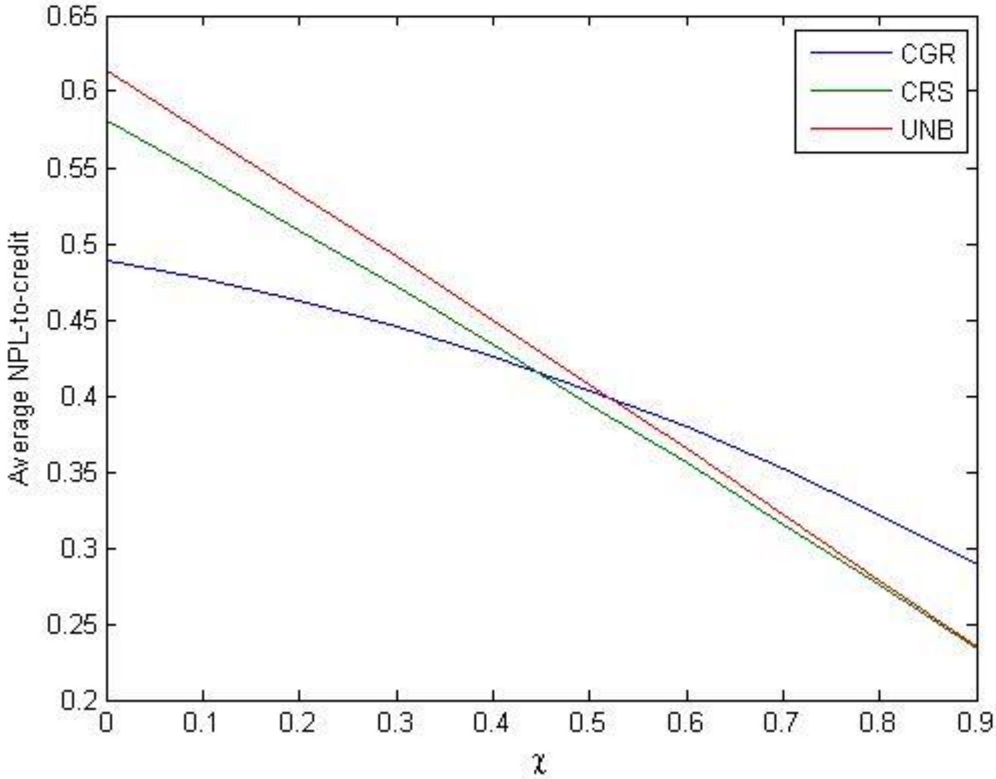

Leverage
t
Δ = -0.5 p.p.
Δ = -0.2 p.p.
Δ = -0.1 p.p.
Δ = 0
Δ = 0.1 p.p.
Δ = 0.2 p.p.
Δ = 0.5 p.p.


NPL-to-credit
t
Δ = -0.5 p.p.
Δ = -0.2 p.p.
Δ = -0.1 p.p.
Δ = 0
Δ = 0.1 p.p.
Δ = 0.2 p.p.
Δ = 0.5 p.p.

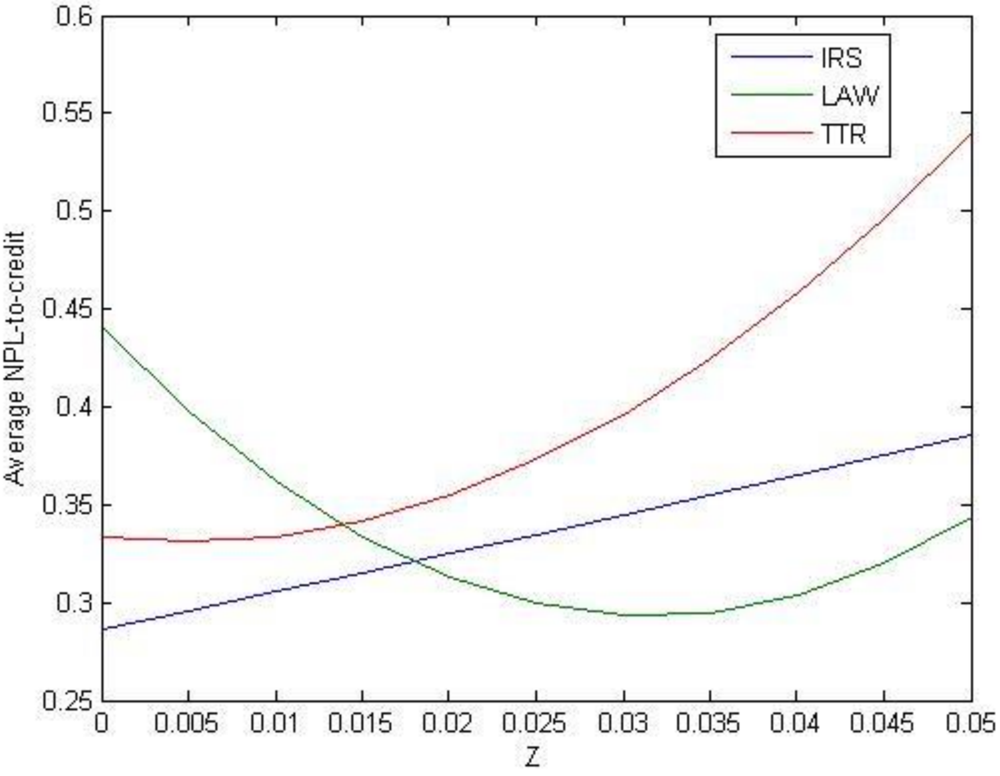
Figures 4a-c

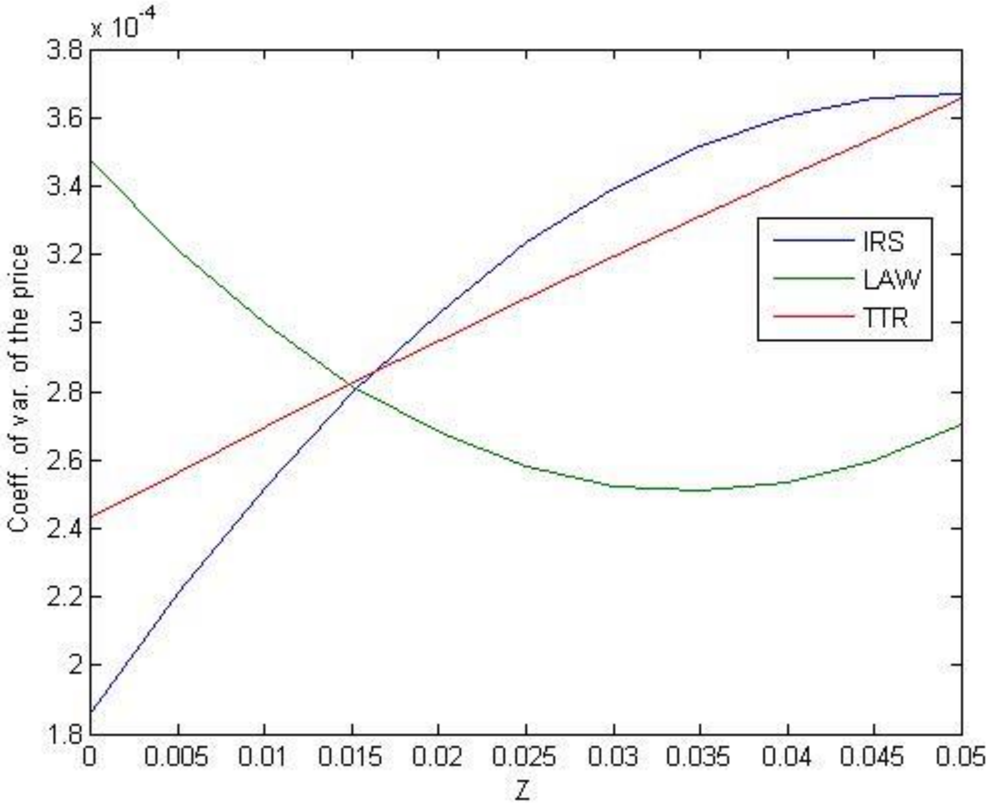

x 10^-4
5
4.5
4
3.5
3
2.5
2
1.5
Coeff. of var. of the price
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
χ
CGR
CRS
UNB

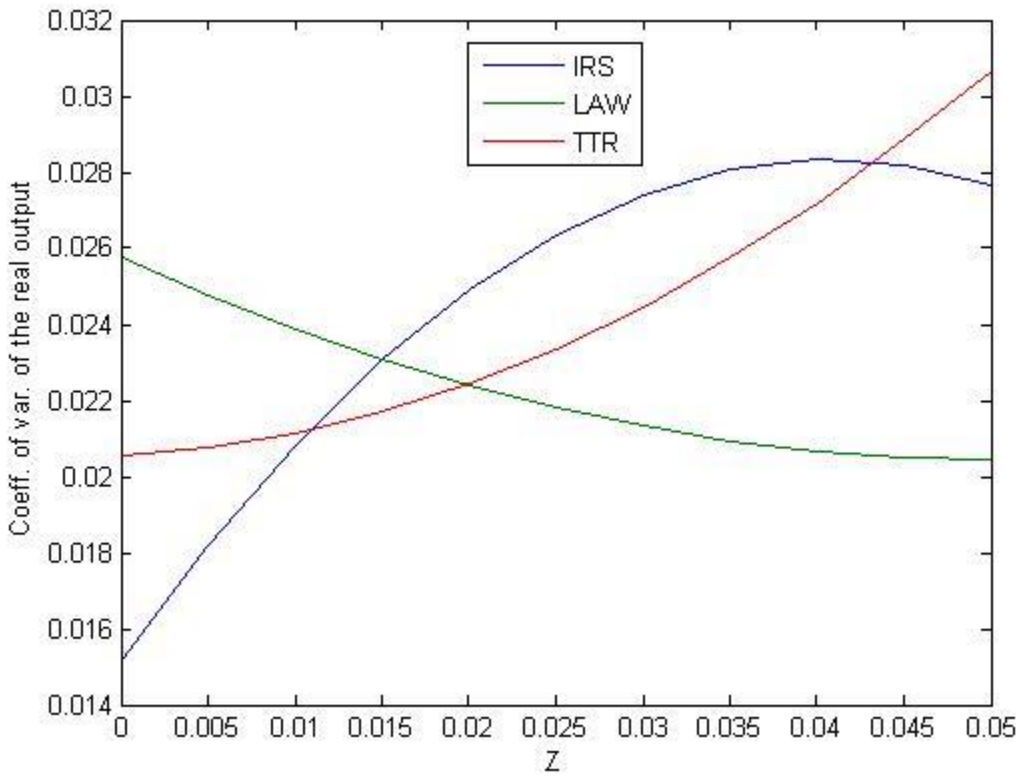

0.04
0.035
0.03
0.025
0.02
0.015
Coeff. of var. of the real output
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
χ
CGR
CRS
UNB


0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
Average NPL-to-credit
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
χ
CGR
CRS
UNB

Figures 5a-c


IRS
LAW
TTR
Average NPL-to-credit
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Z


x 10^-4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
Coeff. of var. of the price
IRS
LAW
TTR
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Z


0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
Coeff. of var. of the real output
IRS
LAW
TTR
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045
0.05
Z