Macroprudential Policy Interactions in a Sectoral DSGE Model with Staggered Interest Rates

Marc Hinterschweiger[a], Kunal Khairnar[b], Tolga Ozden[c], Tom Stratton[a*]

February 15, 2020

Abstract

We develop a two-sector DSGE model with a detailed banking sector along the lines of Clerc et al. (2015) to assess the impact of macroprudential tools (minimum, countercyclical and sectoral capital requirements, as well as and LTV limit) on key macroeconomic and financial variables. The banking sector features residential mortgages and corporate lending subject to staggered interest rates à la Calvo (1983), which is motivated by the sluggish movement of lending rates due to fixed interest rate loan contracts. Other distortions in the model include limited liability, bankruptcy costs and penalty costs for deviations from regulatory capital. We estimate the model using Bayesian methods based on quarterly U.K. data over 1998Q1-2016Q2. Our contributions are threefold. We show that: (i) coordination of macroprudential tools may have a welfare-improving effect, (ii) macroprudential tools would have improved some macroeconomic indicators but not have prevented the Global Financial Crisis altogether, (iii) staggered interest rates may alter the transmission of macroprudential tools that work through interest rates.

Keywords: Sectoral DSGE model; macroprudential policy; interest rate stickiness.

1 Introduction

In the aftermath of the Great Recession, many regulators around the world added policy instruments to their toolkit designed to moderate the effects of future financial crises on the real economy (for on overview, see BCBS, 2019). In the United Kingdom this included the creation of a Financial Policy Committee (FPC), with powers to set a range of macroprudential policies. The policies include capital tools, such as the ability to set a countercyclical capital buffer (CCyB) for the UK on top of banks' minimum (static) capital requirements and higher sectoral capital requirements (SCRs) on residential and commercial property as well as intra-financial

[*a] Bank of England, [b] University of Toulouse, [c] University of Amsterdam.

exposures. The FPC also has powers over loan-to-value (LTV) and debt-to-income (DTI) limits for owner-occupier mortgages, and LTV and interest coverage ratio limits for buy-to-let mortgages, secured on properties in the UK.[1]

We seek to answer several questions in this paper that have arisen regarding the UK macroprudential framework's effects and effectiveness: what is the impact the different tools have on the economy and welfare? How do the different tools interact with each other? What are the main channels of transmission through which these policies operate? Are regulators better equipped to face the next financial crisis? A better understanding of these issues can help regulators to fine-tune their toolkit, understand how best to deploy their policies, and assess any unintended consequences. In particular, knowledge of how the different tools may interact with each other when used in combination is currently limited. Assessing the interactions and coherence among different policies is also part of the Basel Committee's work programme for evaluating and monitoring the impact of post-crisis reforms.[2]

To provide insight on these questions we build a dynamic stochastic general equilibrium (DSGE) model based on Clerc et al (2015), featuring a detailed banking sector, various financial frictions and a macroprudential toolkit. The model comprises of both a housing and corporate sector. Prudential policies include minimum capital requirements, which can vary by sector (akin to an SCR), the CCyB, and LTV limits. We estimate the model using Bayesian methods based on quarterly U.K. data from 1998 Q1 to 2016 Q2.

We pay particular attention to modelling the role of interest rates in the transmission mechanism of macroprudential policies through the introduction of interest rate stickiness. Interest rates likely play a crucial role in determining the impact of policy interventions. For example, the implications of an increase in capital requirements will depend on the extent to which banks pass on the increase in funding costs to interest rates faced by borrowers.[3] Most academic papers in the DSGE literature assume (at least implicitly) that interest rates adjust instantaneously, i.e. interest rates are not subject to any frictions.[4] In contrast, the idea of price stickiness in the goods market is a key aspect of and widely implemented in New Keynesian models.

Following Kobayashi (2007), interest rate stickiness could arise for two different reasons. First, there may be adjustment costs with respect to making changes to loan rates. This may be due to customers' costs of changing banks (switching costs), menu costs of changing interest costs, a highly regulated banking sector or less competitive banking sector. Second, the presence of overlapping multi-period loan contracts with fixed interest rates (for the whole or at least some of the duration of the mortgage contract), could make the adjustment of interest rates sluggish in response to policy actions from a macro perspective.

We model interest rate stickiness by adapting Calvo's (1983) framework for price adjustments to the setting of interest rates for loan contracts. Our preferred interpretation is that, following the second rationale above, many loan contracts in the UK are subject to a specified initial period during which interest rates do not change, for example usually between two to five years in the case of residential mortgages. After the end of this period, the mortgages revert

[1] For a complete list of the FPC's powers, see www.bankofengland.co.uk/financial-stability

[2] See www.bis.org/bcbs/bcbs_work.htm, accessed 14 February 2020

[3] Of course, these costs need to be weighed against the benefits of higher capital requirements, i.e. a reduction in the probability and severity of financial crises. Determining the optimal level of capital requirements is not in scope of this paper.

[4] Some notable exceptions include Gerali et al (2010) and Darracq Pariès et al (2011).

to a floating rate, unless the respective borrower is able to remortgage.[5] As a consequence, the effective interest rate, i.e. the average interest rate on all of a bank's outstanding loan contracts, does not change instantaneously in response to factors that affect the level of the interest rates, such as external shocks or monetary and macroprudential policies.

Our contributions to the literature are threefold. First, we find that the coordination (i.e. joint optimisation) of macroprudential tools may have a welfare-improving effect, compared to optimising each tool in isolation. Second, we perform a counterfactual exercise with the optimal policy settings. Our analysis indicates that macroprudential tools would have improved some macroeconomic indicators, but they would not have been able to prevent the Global Financial Crisis altogether. Third, our results suggest that interest rate stickiness plays an important role for the transmission of shocks through the economy and for the effectiveness of macroprudential tools that work through interest rates.

The paper is organised as follows. The remainder of section 1 reviews the existing literature and provides an econometric rationale for staggered interest rate contracts in the UK. Section 2 describes the model, while section 3 sets out the estimation methodology. In section 4, we analyse the effects of macroprudential policy tools on household welfare and other economic variables. Section 5 discusses the effects of individual shocks on key variables through impulse response functions, with a particular focus on the role of interest rate stickiness. Section 6 concludes.

1.1 Literature review

The literature on the role of banks in DSGE models and financial frictions has been growing rapidly since the financial crisis of 2008. Our model attempts to bring together two streams of the literature. One is based on the seminal paper by Bernanke, Gilchrist and Gertler (1999, subsequently referred to as BGG), where some fraction of borrowers default in equilibrium. Borrowers default due to limited liability and shocks (both aggregate and idiosyncratic) which cause the value of the asset to fall below the loan amount. The other stream of literature is based on borrowing constraints as in Kiyotaki and Moore (1997).

Several papers have built on the BGG framework to include a role for the banking sector. As in BGG, most papers assume that the return on debt is state contingent, implying that banks or financial intermediaries make a risk free return. Thus, in these models, there is no role for bank capital. Clerc et al (2015) depart from this assumption, and develop a model where banks are exposed to risk and can default in equilibrium. Banks are also prone to taking higher risk due to limited liability and deposit insurance. Their model features a meaningful trade-off between the cost of banking sector defaults on the one hand and higher cost of capital on the other. This enables a normative as well as positive analysis of bank capital requirements.

Our paper is based on Clerc et al (2015). Our main extensions are the introduction of staggered interest rate contracts, LTV limits, and a penalty cost function for deviations from regulatory capital requirements. This set-up allows us to analyse the interaction between the capital instruments and borrowing constraints. Benes and Kumhof (2014) also develop a model that features both borrower and bank level default. They study the role of a countercyclical capital policy in a monetary economy and find significant welfare gains. Hodbod et al (2016)

[5] We therefore refer to interest rate stickiness in this paper also as staggered interest rates, but use the terms interchangeably.

develop a similar model and show how a countercyclical risk weight can be used as a macroprudential tool to attenuate the financial cycle. Lozej et al (2017) evaluate different rules for setting countercyclical buffers in a small open economy model for the Irish economy.

The other stream of literature on financial frictions pertains to models with borrowing constraints in the form of a collateral constraint as in Kiyotaki and Moore (1997). Iacoviello (2005) builds a DSGE model with a housing sector and collateral constraints to analyse the transmission of monetary policy. Mendoza and Bianchi (2008) and Jeanne and Korinek (2008) provide a rationale for macroprudential policies due to a pecuniary externality associated with collateral constraints. Gerali et al (2010) explore the role of banking sector related shocks in a model with binding collateral constraints.

In this paper, we bring together these elements, so that borrowers (and banks) can strategically default and borrowers are subject to a collateral constraint on new loans (which appears in the model as an LTV limit). The advantage of this approach is that the collateral constraint can be looked upon as a LTV limit imposed by the bank as well as a policy instrument of the regulator. Another paper that attempts to do so is Nookhwun and Tsomocos (2017). They attempt to explain the financial crisis with default risk shock and a risk premium shock in a DSGE model, similar to Clerc et al (2015). They analyse the role of macro prudential policy tools such as countercyclical capital buffers, LTV limit and state contingent LTV limit.[6]

Few papers look at different prudential policies in the same model. For example, Boissay and Collard (2016) study the transmission mechanism of liquidity and capital regulations in a DSGE model. They find that both policies reinforce each other and support Basel III's "multiple metrics" approach. Goodhart et al (2013) study multiple financial regulations in an integrated framework using a simplified model. They analyse combinations of capital regulations, margin requirements, liquidity regulation, and dynamic provisioning to achieve financial stability and maximise welfare. Popoyan et al (2017) develop an agent-based model to study the macroeconomic impact of macroprudential regulations and their possible interactions with alternative monetary policy rules. In terms of interest rate stickiness, to our knowledge, Gerali et al (2010) and Darracq Pariès et al (2011) are the only other papers to model sticky interest rates in a DSGE framework in a similar fashion.

We explore one of the sources of interest rate stickiness related to the nature of the loan contract, i.e. fixed interest rate loans, in the empirical section of this paper.[7] The existence of fixed rate contracts and longer term loan contracts has been neglected by the literature, with some notable exceptions, such as Bluwstein et al (2018) and Greenwald (2017). However, there is a broader empirical strand of the literature from the 90s that assesses how interest rates adjust. For example, the presence of a highly regulated or less-competitive financial sector (Hannan and Berger, 1991, Neumark and Sharpe, 1992), administrative/menu costs in changing loan rates (Mester and Saunders, 1991), and customers' costs of changing banks (Neumark and Sharpe, 1992). Lowe and Rohling (1992) provide theory and evidence on interest rate stickiness. They consider theories that are based on equilibrium credit rationing, switching costs, implicit risk sharing and consumer irrationality. Their empirical evidence provides support for the switching cost explanation. More recently, Driscoll and Judson (2013) examine the dynamics of eleven different deposit rates for a panel of over 2,500 branches of about 900 depository institutions

[6]Other papers with a key role for banking sector within a DSGE framework include Goodfriend and McCallum (2007), Curdia and Woodford (2008), Meh and Moran (2010), and Cristiano, Motto and Rostagno (2014).

[7]For the sake of clarity, the interest rate stickiness in this paper is with respect to lending rates and not with respect to monetary policy rates or Taylor rule inertia as in Rudebusch (2000, 2006).

observed weekly over ten years. They find that rates are downwards-flexible and upwards-sticky, and show that a simple menu cost model can generate this behaviour. Bernstein and Fuentes (2004) provide evidence that the lending rates in Chile are flexible as compared to most other countries. Moazzami (2010) finds that lending rates in the US have been stickier than those in Canada. However, the US lending rate rigidity, has decreased in recent years. Sorenson and Werner (2006) investigate the pass-through between market interest rates and bank interest rates in the euro area. They find heterogeneity in interest pass through across loan products and that the speed of adjustment of interest rates is slow. Nakajima and Teranishi (2009) show that the loan rates are sticky with respect to the policy interest rate in all Eurozone countries for all loan maturities, the degree of stickiness differs across the countries, and the degree of difference is more prominent for longer loan maturities. Andries and Billon (2014) provide a survey of the empirical literature on interest rate pass-through. The results show that although there is complete long run pass-through of interest rates, there is incomplete short-run pass-through and a heterogeneous adjustment of bank interest rates across bank products and euro zone countries.

1.2 Interest Rate Stickiness in the U.K.

Although interest rate stickiness could arise due to number of reasons highlighted by the literature such as market power, level of competition, regulation, switching/menu costs etc, we highlight the importance of interest rate stickiness emanating from the nature of loan contract i.e. existence of long term loans and fixed interest loans.

In this section, we compare the response of (effective) lending rates for different terms of interest rate fixation to changes in policy rates. Figure 1 depicts the movement of mortgage rates (for different maturities) over the period of last 20 years in the UK.

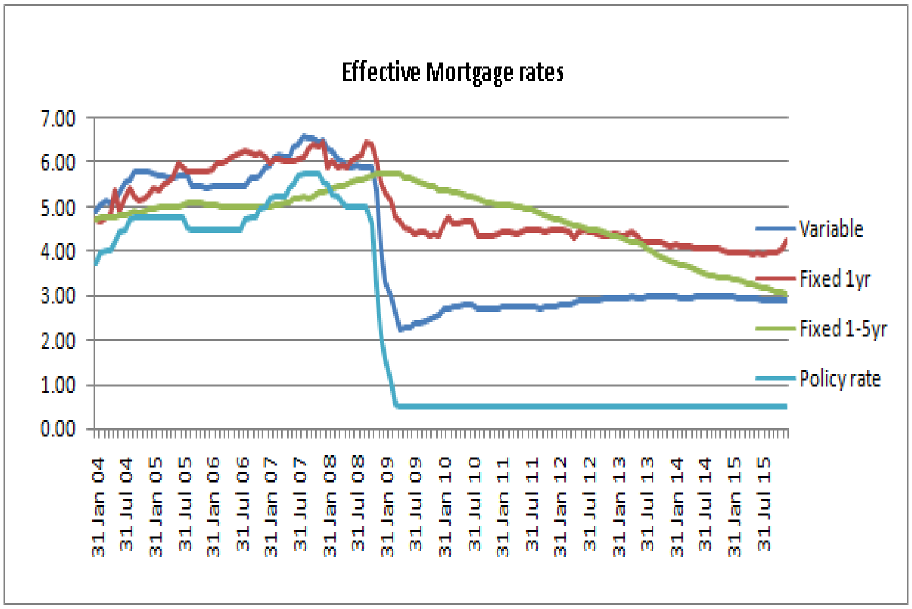
We use monthly data on effective interest rates (between January 2004 to January 2016) for mortgage loans in the United Kingdom (for different terms of interest rate fixation) from the Bank of England statistics website. As can be seen in the figure below, the response of effective variable interest rate mortgages (to changes in the policy rate) is faster than the effective fixed interest mortgages (as expected). In general, the response of fixed interest mortgages decreases the longer the initial fixed portion of the loan contract. The effective interest rate of a given portfolio of loans is based on a mix of older loans (which are being repaid over time), which pay an interest rate that was fixed in the past, whereas the newest loans pay interest at the current market rates. As a result, even if the market interest rates change, the effective interest rates would not fully adjust immediately. They change slowly as the older loans are repaid and new loans are added to the loan portfolio over time.

Interest rate stickiness can vary across different sectors, depending upon the proportion of long term contracts in the portfolio. Figure 1 contrasts the different degrees of stickiness in the case of mortgage loans and business loans. We find that the interest rate pass-through is slower for the mortgage loan portfolio as compared to the business loan portfolio.

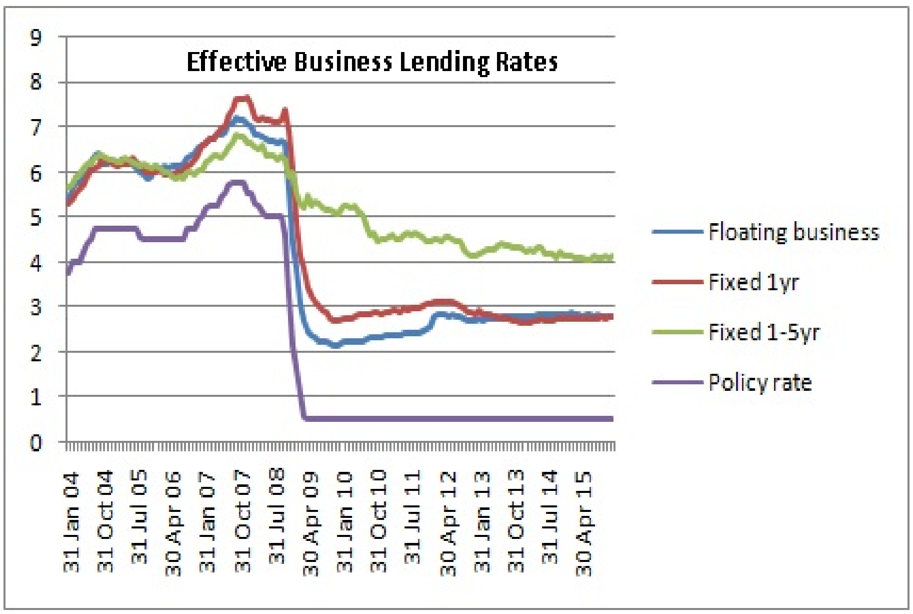
1.2.1 Econometric Methodology

As a first step to investigate the extent of stickiness in the movement of interest rates, we assess econometrically how lending rates change in response to a change in the central bank policy rate. Following the empirical literature on interest rate pass-through, we run a vector error

Figure 1: Monthly lending rates in the U.K. between periods 2004-2015.



(a) Mortgage lending rates.



(b) Corporate lending rates.

correction model, where policy interest rates are considered to be the most direct determinants of retail bank lending rates. We run the following vector error correction model based on Johansen (1991):

$$\Delta R_t = \sum_{k=1}^{K} \delta_k \Delta R^m_{t-k} + \sum_{q=0}^{Q} \gamma_q \Delta i_{t-q} + \alpha(\mu + R^m_t - \beta i_t) + u_t \tag{1.1}$$

where R_t is the effective lending rate (mortgage loans), i_t is the Bank of England policy interest rate, the coefficient β is the long run equilibrium relationship between bank lending rate and policy rate and the coefficient α is the speed of adjustment of the lending rate to the long run equilibrium. The coefficients of the lags of the first difference of the policy rate capture the short-run response of mortgage lending rates to the policy rate. We conduct this exercise for three different lending rates: a variable interest rate, a fixed interest rate for a term of up to 1 year, and a fixed interest rate for a term of 1 to 5 years. The results are summarised in the following table.

Table 1: Regression of UK Bank lending rate on BoE policy rate

Regressor	Floating rate	Fixed < 1 year	Fixed 1 to 5 year
γ_0	0.016***	0.0057	0.0025
γ_1	0.896***	0.435***	0.018
γ_2	0.016	-0.293***	-0.0158
γ_3	-0.008	0.242***	0.0097
γ_4	-0.196***	-0.037	0.0054
constant	0.1366***	-	-

In the case of floating interest rate loans, the response on impact is very low. However, around 90 percent of the pass-through takes place in the following month. The above table highlights that the response of floating interest rates to the central bank policy rate, as depicted by coefficients $\{\gamma_j\}_{j=1}^{4}$, is higher than the response of 1 year fixed rate loans, which in turn is higher than the response of the 1 to 5 year fixed rate loans. In case of fixed term loans of up to 1 year, the response on impact is very low (less than 0.01 percentage points) and around 45 per cent of the pass-through takes place in the following month.

The pass-through for the 1 to 5 year fixed term loans is very low. However, there exists a long term co-integration relationship between the two interest rates. For the fixed rate loans, the sum of short run coefficients is less than 1, suggesting an incomplete pass-through of the policy interest rate.

Thus, the pass-through to the fixed interest loans is not only sluggish but also incomplete, whereas the pass-through to variable interest rate loans is faster and almost complete. However, in all cases with floating interest rate, the response of the lending rate on impact is very low (less than 2 percent).

The fact that floating interest rates adjust faster than the fixed term interest rates implies that the existence of fixed rate contracts is an important source of interest rate stickiness.

2 Model Summary

Our model closely follows Clerc et al. (2015), which augments the baseline model of Bernanke, Gertler and Gilchrist (1999) with a detailed banking sector and different types of default of households, corporates and banks to determine the optimal capital adequecy ratio (CAR) for the

[7]*** is 1 per cent, ** is 5 per cent and * is 10 per cent level of significance

banking sector, as well as to analyze the macroeconomic implications of bank capital structure under different shocks.

The BGG framework assumes that interest rates charged by the banks are state contingent. This implies that higher interest rates charged on non-defaulters are sufficient to meet the losses arising from defaulters. This means that banks always make a risk-free return on their investments, which makes the capital structure of the bank irrelevant in the original BGG framework. Clerc et. al. (2015) departs from the BGG framework by assuming a non-contingent lending rate, which implies that in the event of defaults by borrowers, banks may also suffer losses. Therefore, with costly state verification of borrowers, defaults are costly and entail a dead-weight loss for the economy, which necessitates a role for bank capital. They further assume that investor wealth is scarce and hence cost of equity capital is higher than debt funding. This implies that although bank capital is necessary to avoid higher default rates, it is also expensive at the same time, thus creating a trade-off for holding capital.

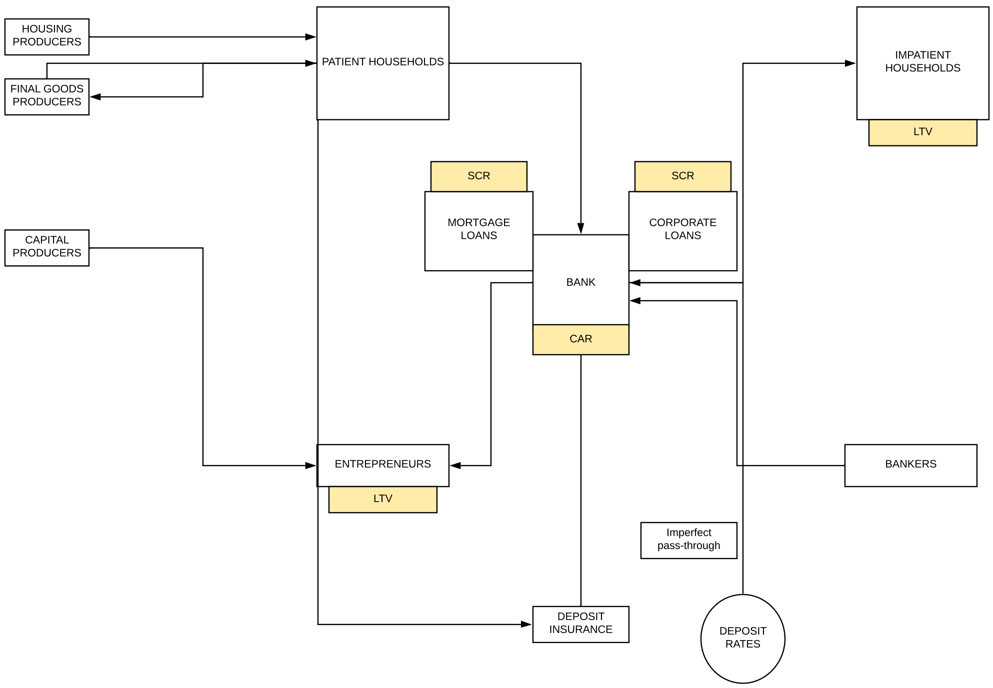
Our model deviates from Clerc et. al. (2015) in several important ways. On the banking side, we introduce staggered interest rates à la Calvo (1983) to capture the stickiness of mortgage and corporate lending rates, which is motivated by the empirical evidence shown in Section 1.2. Further, we endogenize the bank's capital level by allowing it to be determined in equilibrium through the bank's decision problem. Accordingly, the bank maximizes over its lending rates to households and businesses subject to interest rate stickiness. The minimum and sectoral capital requirements are introduced as penalty costs on the bank's decision problem, which creates a precautionary motive for the bank to hold a capital level higher than the minimum required. This is a realistic setup since banks typically maintain capital buffers to ensure they do not breach the regulatory minimum. This differs from Clerc et. al. (2015), which assumes that banks always hold the minimum capital requirement[8].

We introduce exogenous loan-to-value (LTV) limits in the household and corporate sectors on the flow of new lending. The LTV limits are qualitatively similar to an exogenous collatoral constraint as in Iacoviello (2015). Our main focus in this paper is on the household LTV limit, since the Financial Policy Committee (FPC) in the U.K. does not have such a regulatory tool on corporate lending. Other key distortions and frictions in the model closely follow Clerc et. al. (2015), i.e. both the bank and borrowers (mortgage or corporate) in the model are subject to limited liability. The limited liability of banks, along with the presence of a deposit insurance agency, implies that banks have an incentive to over-borrow and over-lend, since they do not fully internalize the costs of default. In this framework, regulatory capital is a means to restrict the use of excessive bank leverage. The model further features costly state verification, which implies that the use of leverage is more expensive and that defaults are costly.

The key agents in the economy are patient and impatient households, entrepreneurs, a bank that lends in the corporate and mortgage sectors, a deposit insurance agency, and housing, capital and final goods producers. Figure 2 provides an overview of the main interactions between these agents along with the regulatory tools present in the model. Below we summarize the maximization problems for each agent type, while the associated first-order conditions and further details can be found in Appendix D.

[8]Another minor deviation in our setup is that there is only one bank in our model than lends in the corporate and mortgage markets, rather than two sectoral banks as in Clerc et. al. (2015).

Figure 2: An overview of the main actors and regulatory tools in the model.



2.1 Overview of Agents

Households: there are two types of households, patient and impatient, with patient households having a higher discount factor, as in Iacoviello (2015). Both patient and impatient households have concave utility functions and derive utility from consumption goods, housing and leisure. The individual households are a part of a representative dynasty, which provides perfect risk sharing within the group. Thus, all individual households within the type are ex-ante identical. While the individuals face idiosyncratic shocks, they are perfectly insured within their dynasty and hence consume and save/borrow identically. Both households supply labour in a competitive labour market.

Patient households are savers who supply deposits to the bank in equilibrium, and buy houses with their own funds. Both household types derive utility from consumption as well as housing goods, and dis-utility from labour. As such, the patient household's maximization problem is given as:

$$\max_{c_t^s, L_t^s, D_t, H_t^s} E_t \sum_{t=0}^{\infty} \beta_s^t [log(c_t^s) + vlog(H_t^s) - \frac{(L_t^s)^{1+\eta}}{1+\eta}] \tag{2.1}$$

subject to the following budget constraint:

$$c_t^s + q_t^H H_t^s + D_t = w_t L_t^s + q_t^H H_{t-1}^s (1-\delta) + D_{t-1} R_t^D + \pi_t \tag{2.2}$$

where π_t includes profits of final goods producing firms and investment and housing production firms (which are owned by patient households), dividends from entrepreneurs and lump-sum transfers from the deposit insurance agency.

Impatient households borrow from banks using their houses as collateral. Mortgage loans are made on a limited-liability basis, which implies that individual households can default whenever the value of their house is lower than the outstanding mortgage loans. The value of the house depends both on aggregate shocks, which affect the value of their house, as well as idiosyncratic shocks which affect the default decision of individual borrowers. In equilibrium, borrowers with an idiosyncratic shock below a certain threshold default, in which case the bank takes possession of the house subject to a state verification cost.

We introduce a loan-to-value (LTV) limit set by the macroprudential regulator on the flow of new lending, which is similar to a collateral constraint as in Kiyotaki & Moore (1997). With the exception of having a different discount factor, the impatient household has the same objective function as the patient household, which is given as follow:

$$\max_{c_t^m, B_t^m, L_t, H_t^m} E_t \sum_{t=0}^{\infty} \beta_m^t [log(c_t^m) + vlog(H_t^m) - \frac{(L_t^m)^{1+\eta}}{1+\eta}] \tag{2.3}$$

subject to the following budget constraint, which reflects their borrowings under limited liability:

$$c_t^m + q_t^H H_t^m - B_t^m = w_t L_t^m + \int_{\bar{\omega_t^m}}^{\infty} \left(\omega_t^m q_t^H H_{t-1}^m (1-\delta) B_{t-1}^m R_{t-1}\right) dF\omega_t^m + P_t \tag{2.4}$$

The term under the integral reflects the limited liability of the borrowers as they default on their loans when the idiosyncratic shock ω_t^m is below the threshold level of $\bar{\omega^m}_t$. The default threshold of the borrowers is determined by:

$$\bar{\omega^m}_t q_t^H H_{t-1}^m (1-\delta) = B_{t-1}^m R_{t-1}^m \tag{2.5}$$

Finally, the LTV limit (or the borrowing constraint) is given by:

$$[B_t^m - (1-rp)B_{t-1}^m] R_t <= \epsilon_t E_t[q_{t+1}^H [H_t^m - H_{t-1}^m (1-\delta)]] \tag{2.6}$$

where rp denotes the loan repayment rate and ϵ_t is the LTV limit. We assume that the LTV limit always binds in the steady state and its neighbourhood.

Entrepreneurs are risk neutral agents who own and maintain the stock of physical capital. They rent capital to the final goods producing firms. Entrepreneurs derive utility from transferring part of their wealth to the saving dynasty by paying out dividends and retaining the rest for the next period as retained earnings. Entrepreneurs invest in capital goods and finance their investment by means of their own funds, i.e. net worth, and borrowings from banks. Similar to mortgage loans, these are limited liability loans and hence subject to default by individual entrepreneurs in the event of the value of assets falling below the value of outstanding loans. The value of the capital depends both on aggregate shocks as well as idiosyncratic shocks, which affect the default decision. In equilibrium, entrepreneurs with an idiosyncratic shock below a certain threshold default. As in the case of households, assets are seized by banks and subject to costly state verification costs. The entrepreneurs' decision rule is given as follows:

$$\max_{K_t, B_t^e} E_t(W_{t+1}^e) \tag{2.7}$$

with

$$W^e_{t+1} = max[\omega^e_{t+1}(r^k_{t+1} + (1-\delta)q^K_{t+1}K_t) - R^F_t b^e_t, 0] \tag{2.8}$$

The default decision of the entrepreneurs is determined by:

$$\bar{\omega^e}_t q^K_t K^m_{t-1}(1-\delta) = B^e_{t-1}R^f_{t-1} \tag{2.9}$$

Similar to the impatient households, entrepreneurs are subject to the following LTV limit on the flow of new borrowing:

$$[B^e_t - B^e_{t-1}(1-rp)]R^f_t = \epsilon_t E_t[q^F_{t+1}[K_t - K_{t-1}(1-\delta)]] \tag{2.10}$$

A fixed proportion of wealth χ^e is paid out as dividends. This simple dividend paying rule for the entrepreneurs is given by:

$$c^e_t = \chi^e W^e_t \tag{2.11}$$

As a result, the retained earnings by the entrepreneurs is given by:

$$n^e_t = (1-\chi^e)W^e_t \tag{2.12}$$

The balance sheet identity of the entrepreneurs follows as:

$$n^e_t + B^e_t = q^K_t K_t \tag{2.13}$$

Banks are financial intermediaries who channel savings from the savers to the borrowers. On the asset side of the banks, there are loans to households (mortgage lending) and entrepreneurs (business lending) respectively. As described earlier, these loans may default depending on aggregate state shocks and idiosyncratic borrower shocks in which case the banks seize the assets subject to state verification costs, which can also be viewed as bankruptcy costs.

On the liability side of the banks, there are deposits held by the patient households and equity capital held by the bankers. Deposits are insured by the Deposit Insurance Agency (DIA). There is a capital adequacy requirement set by the regulator which, along with a penalty cost function, determines the amount of equity capital held by the bankers.

One of the key features of the model is that banks may also default depending on the performance of their loan portfolios, which is driven by an aggregate shock and idiosyncratic shocks similar to the impatient households and entrepreneurs. The banks face an idiosyncratic shock to their returns on loans and therefore, in equilibrium, a fraction of banks below a certain threshold of the idiosyncratic shock level default. In case of default, the bank loan assets are possessed by the DIA, subject to costly state verification.

The banks' balance sheet identity is as follows:

$$n^b_t + D_t = B^m_t + B^e_t \tag{2.14}$$

Their optimisation problem is given by:

$$\max_{R^{mi}_t, R^{fi}_t} E_t \sum_{t=0}^{\infty} \xi^t \beta^t_s [\{(1-G^H_{t+1})(\widetilde{R^{mi}_t})(B^{mi}_t) + (1-G^F_{t+1})\widetilde{R^{fi}_t} B^{ei}_t\} - (1-F^)R^D_t D_t + Penaltycost] \tag{2.15}$$

$$\widetilde{R^{mi}_t} = (1 - E_t F^m_{t+1})R^{mi}_t + E_t G^m_{t+1}(1-\mu^m)(R^{mi}_t / E_t \bar{\omega}^m_{t+1}) \tag{2.16}$$

$$\widetilde{R_t^{fi}} = (1 - E_t F_{t+1}^e) R_t^{fi} + E_t G_{t+1}^e (1 - \mu^e)(R_t^{fi} / E_t \bar{\omega}_{t+1}^e) \tag{2.17}$$

The demand for loans is given by:

$$B_t^{mi} = (\frac{R_t^{mi}}{R_t^m})^{-\tau} B_t^m \tag{2.18}$$

$$B_t^{ei} = (\frac{R_t^{fi}}{R_t^f})^{-\tau} B_t^e \tag{2.19}$$

Penalty costs for violating the regulatory requirements are modeled as a non-pecuniary gain in utility if the capital adequacy ratio is higher than the minimum capital requirement and a non-pecuniary cost if the capital adequacy ratio is lower than the minimum capital requirement with the following functional form:

$$PC_t = \nu^b \frac{[\frac{\phi_t^b}{\bar{\varphi}_t}]^{1-\sigma} - 1}{1 - \sigma} \tag{2.20}$$

which is based on Nookhwun & Tsomocos (2017). The marginal gains of having excess capital are decreasing, whereas the marginal costs of having a shortfall in capital are increasing, whenever σ is greater than 1. This creates an incentive for banks to maintain capital at a higher level than the minimum regulatory requirement. In reality, we find that banks do maintain capital buffer over what is the minimum required, see e.g. Nier and Baumann (2006). The parameter ν^b determines the weight attached to these penalty costs.

Staggered interest rates: while we find that one of the main sources of interest rate stickiness is the existence of fixed-interest rate loans as shown by our empirical exercise in Section 1.2, interest rate stickiness can be attributed to various reasons such as switching or menu costs, market structure, regulation and so on. Therefore we introduce interest rate stickiness in a broader sense by modeling it as in Calvo (1983). This approach has the benefit of including many possible sources of interest rate stickiness in a reduced form. As such, we assume that only a proportion of 1-ξ of banks are able to change their lending rates in a given period, whereas the remaining proportion ξ are unable to change their lending rate, which remains fixed at the previous period's value. Accordingly, the composite interest rate in the economy is a weighted average of the current interest rate charged by the banks that can change their interest rate, and the previous period's interest rate used by the banks that cannot change their interest rate.

In order to micro-found the staggered interest rate setting, we assume that there is imperfect competition in the banking sector, where banks offer differentiated loan products as in Gerali et. al. (2010) and are able to set their interest rate in the monopolistically competitive loan market. The borrowers then take a composite loan product consisting of these differentiated banking services. The first-order conditions of the bank for interest rates resemble the first-order conditions for prices in a standard New Keynesian setting with price stickiness, and they are given as:

$$R_t^{mi} = \frac{\tau}{\tau - 1} \frac{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t MC_t}{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t rm_t} \tag{2.21}$$

$$R_t^{fi} = \frac{\tau}{\tau - 1} \frac{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t MC_t}{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t rf_t} \tag{2.22}$$

$$MC_t = \lambda_{st+1}[(1 - F_t^B)R_{Dt} + \frac{\nu^b(\phi_t^b/\bar{\varphi}_t)^{(1-\sigma)}}{(B_t^{mi} + B_t^{ei})}](R_t^m)^\tau B_t^m \tag{2.23}$$

where the interest rate charged by banks is a function of the present discounted value of present and future "marginal cost" (MC) times the mark-up, where the MC includes the interest rate paid on deposits in a competitive deposit market, and the penalty cost associated with deviating from regulatory capital requirements.

Deposit Insurance Agency insures the deposits, where the assets of the defaulting banks are taken over by the agency and are subject to bankruptcy costs. The difference between the amount of deposits and the value of realized assets is recovered by imposing a lump-sum tax on households.

Final goods producing firms are modeled as a unit mass of perfectly competitive firms, which combine capital and labour to produce the consumption good. The firms rent capital from entrepreneurs, and they are owned by patient households. They produce the final goods using a standard Cobb-Douglas technology:

$$Y_t = E_{A_t} K_{t-1}^\alpha L_t^{1-\alpha} \tag{2.24}$$

Capital goods and housing production comes from competitive firms, owned by patient households, that buy finished goods and produce capital goods and housing subject to quadratic adjustment costs. These firms produce new units of capital and housing using consumption goods, which are then sold to entrepreneurs and households. As such, they represent the supply side of capital goods and housing, and they pin down the equilibrium asset prices.

2.2 Exogenous Processes

The model is equipped with 12 exogenous AR(1) processes across different sectors. On the housing side, we have two preference shocks on housing and consumption $E_{J,t}$ and E_{C_t}, which affect the taste of both patient and impatient households for consumption and housing goods, respectively. These shocks can be equivalently interpreted as the degree of risk aversion to purchasing consumption and housing goods. We further have a housing price shocks $E_{H,t}$, which is an external shock that directly affects the housing price index[9]. Finally, we have a shock on the LTV limit of the households, $E_{LTVH,t}$ which is introduced in order to relax the restrictiveness of an always binding constraint.

On the corporate side, we have a net worth shock $E_{We,t}$, which is a transfer from the housing sector to the businesses, which can be thought of as a proxy for an exogenous government spending shock in our model. We also introduce a risk shock $E_{Se,t}$ into the corporate sector, which affects businesses' likelihood of default. Finally, we have an expected capital price shock $E_{EbF,t}$, which drives the stock market sentiment in the model.

On the banking side, we have a bank risk shock $E_{Sb,t}$ that has a similar meaning as its counterpart in the corporate sector. The bank is further subject to a bank capital shock $E_{CAB,t}$, which affects its capital ratio, and two mark-up shocks on its interest rate setting, $E_{markup^m,t}$ and $E_{markup^F,t}$, which affect the cost of mortgage and corporate lending, respectively, for the

[9]This shock can also be thought of as a measurement error, i.e. the component of the housing prices that is not explained internally by the model.

bank. These mark-up or cost-push shocks help introduce a wedge between the realized interest rates and the rates that the bank would use in the absence of interest rate stickiness.

Finally, the Cobb-Douglas production function of final goods producing firms is subject to a productivity shock $E_{A,t}$[10].

3 Estimation

3.1 Measurement equations

We use quarterly data for the U.K. over the period $1998Q1-2016Q2$ for ten key macroeconomic and financial variables[11] for the Bayesian estimation of our model[12]. For aggregate output Y_t, wages W_t, investment I_t, consumption C_t, as well as house prices $q^{H,t}$, corporate lending $b_{e,t}$ and mortgage lending $b_{m,t}$, we match the data in terms of growth rates with a measurement equation of the form:

$$\Delta x_t^{obs} = \gamma_x + X_t - X_{t-1}, \tag{3.1}$$

with $x \in \{Y, W, I, C, q^H, b_e, b_m\}$, where γ_x denotes the historical average of each time series under consideration[13]. For the remaining three variables, namely the official bank rate R_t^D, the effective mortgage lending rate R_t^H, and the effective corporate lending rate R_t^m, we match the data in levels with a measurement equation of the form:

$$y_t^{obs} = 100(\bar{Y} - 1) + Y_t, \tag{3.2}$$

with $y \in \{R^D, R^H, R^m\}$, and $\bar{Y}$ denotes the steady-state level of the associated variables in the model. Note that we match the official bank rate to the deposit rates in the model[14].

3.2 Calibrated Parameters and Prior Distributions

Prior to estimation, we fix a number of parameters by either following conventional values used in the literature or by generating steady-state values consistent with U.K. data. Parameters relating to default costs are based on Mendicino et al. (2015): the depositor cost of bank default γ is fixed at 0.1. The bankruptcy cost of households, businesses and banks μ_m, μ_e and μ_B are set to a common value of 0.3. The discount factor for patient households is 0.995.

[10] We also experimented with different combinations of shocks across different sectors, e.g. a risk shock on the housing sector, an LTV limit shock on the corporate sector, housing and capital depreciation shocks and a net worth shock in the banking sector. The particular set of shocks reported in the paper emerges as the best combination of shocks in terms of model likelihood and providing a reasonable historical variance decomposition for key variables.

[11] Further details on the observable variables can be found in the appendix.

[12] The preceding two years over 1996Q1-1997Q4 are used as a training sample.

[13] Since our model does not feature a steady-state growth, these averages are pre-computed and remain fixed during the estimation.

[14] An alternative approach is to use both the official bank rate and average deposit rates, where the difference between the two is captured with another layer of staggered interest rates. This approach has been adopted in Darracq Pariès et al. (2011), where they find little evidence of staggered rates between these two time series. Therefore in this paper, we directly equate the deposit rates to the official bank rate for simplicity.

For some parameters, we use standard values following the convention in the literature. Accordingly, the capital share in production is set to 0.3, while the Frisch elasticity of labor η is 1. The labour preference parameters for both types of households φ_s and φ_m are normalized to 1 since they mainly scale the size of the economy. The parameters a_s and a_b are set to 0.5, which determine the share of total default costs paid by saving and borrowing households, respectively.

Some parameters are closely linked with the steady-state of the economy. We use these parameters to generate plausible ratios for some of the key variables. The housing preference parameters for both types of households, v_s and v_m, as well as business and bank dividend payout parameters, χ_e and χ_b, are used to generate plausible business and mortgage lending to aggregate output ratios. Accordingly, we set $v_s = 0.25$ and $v_m = 0.5$, while the dividend payouts are set to $\chi_e = 0.1$ and $\chi_b = 0.15$. These generate lending ratios of 133% and 86% for corporate and mortgage lending to output, respectively, which are reasonably close to the historical means of the corresponding U.K. ratios over the estimation period, which are 118% and 81%. At the given values, mortgage lending constitutes 38% of total lending in steady-state. Similarly, we set the housing and capital depreciation rates to $\delta_H = 0.01$ and $\delta_K = 0.04$, which yields an investment to output ratio of 12%, which is close to the historical mean of 17% for the U.K. economy over this period[15]. The parameters determining market power of the bank, τ_m and τ_F, are both set to 40, whereas the hyperparameters in the cost function are set to $\psi_b = 5$ and $\nu = 0.5$. Finally, we set the household and entrepreneur repayment rates in the LTV limit as 0.01 and 0.05, respectively.

Parameters relating to macroprudential regulation are fixed in our benchmark estimations. Accordingly, for minimum capital requirements, we use a benchmark value of $\phi_H = \phi_F = 0.11$ for both sectors, which is close to the historical minimum capital requirements for the U.K.[16]. We assume that there is no CCyB in place in our benchmark estimations, and the LTV limit for households is fixed at 86%, which corresponds to the historical average over most of this period for the U.K. economy[17]. We fix the LTV limit on corporates at the same value as household LTV.

The remaining 33 parameters are estimated using Bayesian likelihood methods to match the data. For the AR(1) coefficients of all exogenous shocks, we use a standard Beta distribution with mean 0.5 and standard deviation 0.2 following Smets-Wouters (2007). The standard deviations of all exogenous shocks are assigned a diffuse uniform prior over the interval $[0, 10]$. The volatility of i.i.d. shocks on households, businesses and banks follow a common Inverted Gamma distribution with mean 0.1 and standard deviation 2: we choose to use more informative priors for these parameters since both aggregate and i.i.d shocks mainly relate to the level of default rates in a first-order approximation, hence estimating both sets of parameters with uninformative priors may lead to identification issues. For the cost adjustment parameters ψ_i

[15] In the model, aggregate investment is calculated as the sum of housing and capital investment. The historical mean ratio for the U.K. is taken from ons.gov.uk for the estimation period.

[16] Available data for capital requirements is taken from Bank of England's website, where we use Basel III common equity Tier I capital ratio after 2014, and Core Tier I capital ratio before 2014. Alternatively, one could use the capital requirements as another observable in the estimation, but we choose to fix these ratios given that Basel requirements do not have a one-to-one correspondence in the model, and that the data is only available at an annual frequency before 2014.

[17] Similar to capital ratios, the data to calculate this average is taken from the BoE's website, where we use the residential mortgage LTV ratio, available over the period 2005-2016.

and ψ_h, we assume a conventional normal distribution with a mean of 5 and standard deviation 2[18]. For habit formation λ, we use the same Beta prior as in Calvo parameters, and for the impatient household discount factor β_m, we use a tight Beta prior with 0.98 and standard deviation 0.01 to ensure that the prior interval for this parameter remains below the patient household discount factor of 0.995. Finally, the volatility of the default shock parameters σ_e, σ_m and σ_B are assigned inverted Gamma priors with mean 0.1 and standard deviation 2[19]. The priors for all parameters are summarized in Table 2.

The steady-state of our model is not available in closed-form and therefore it is numerically computed for every parameter draw. This increases the computational burden associated with the posterior distributions. This complicates the estimation of parameters that affect the steady-state, namely the habit formation, impatient household discount rate, and the i.i.d. shock variances. Therefore, for these five parameters, we only compute the point estimates for the candidate density (i.e. posterior mode). We then leave the parameters fixed at these point estimates before proceeding to the computation of posterior distributions[20].

The posterior distributions of the remaining 28 parameters are computed using 4 parallel Monte Carlo Markov Chains (MCMC), each with 500000 draws, where the first half of each chain is discarded as a burn-in sample. The scaling coefficient of the parameter covariance matrix is adjusted to obtain an acceptance ratio of around 35% in each case.

3.3 Posterior Distributions for Estimated Parameters

The point estimates, along with the 95% highest posterior density (HPD) intervals for the parameters are reported in Table 2[21]. Of particular interest are Calvo parameters, for which the posterior distributions along with the posterior mean and mode are shown in Figure 3. We find a Calvo probability of 49.7% for corporate rates, whereas the probability for mortgage rates is 71.8%. This means, on average, banks are able to reset the interest rates on corporate loans once every 1.98 quarters or 5.94 months, while it takes much longer to reset the interest rates on mortgage loans with an average duration of 3.54 quarters or 10.62 months. The 95 % credible intervals are $[5.19, 6.51]$ for corporate rates and $[8.82, 12.48]$ for mortgage rates.

The shocks are typically estimated with high autocorrelation coefficients, with the exception of bank and entrepreneur risk shocks. In particular, the productivity, housing preference and business net worth shocks have autocorrelation coefficients near unity, implying high persistence. These shocks also emerge as the main drivers of the business cycle for key variables as will be discussed below. For the capital and housing investment adjustment cost parameters, we find values of 7.92 and 4.85 respectively, implying more sluggishnes in housing investment compared with capital investment.

[18] See e.g. Smets-Wouters (2007), which uses a normal prior with mean 4 and standard deviation 1.5. Note that our prior is more diffuse compared to BoE's COMPASS model (2013), which uses a tight Gamma prior with mean 2 and standard deviation 0.4.

[19] These i.i.d. shocks essentially play the same role as the exogenous risk shocks in terms of determining the default rates (with the difference that i.i.d. shocks affect the steady-state levels, while the exogenous shocks do not). Therefore these two sets of shocks may not be jointly identified, therefore we assign more informative priors for these parameters compared to the standard deviation of exogenous shocks.

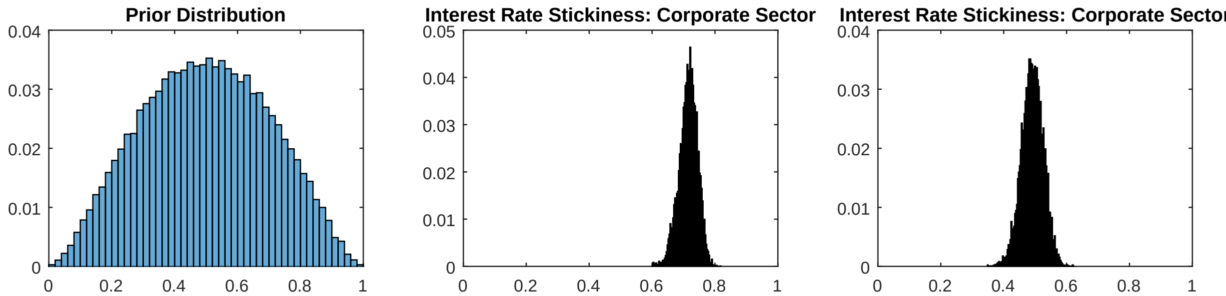
[20] Alternatively, one could fix these parameters similar to the others, but we did not find studies with similar parameters on the U.K. data that could guide the choice of these and therefore took this intermediate approach.

[21] The distributions of all estimated parameters can be found in Appendix C in Figures 18 and 19.

Table 2: Posterior Estimates

Parameter	**Prior**			**Posterior**			
	Dist	Mean	Variance	Mode	Mean	HPD % 5	HPD % 95
ϵ_A	Uniform	10	5.77	0.0078	0.0079	0.0068	0.0092
ϵ_J	Uniform	10	5.77	0.0971	0.1019	0.0841	0.1234
ϵ_H	Uniform	10	5.77	0.0396	0.0499	0.0323	0.0739
ϵ_{Se}	Uniform	10	5.77	0.0462	0.0728	0.0317	0.1483
ϵ_{SB}	Uniform	10	5.77	0.0308	0.0317	0.0244	0.0398
ϵ_{We}	Uniform	10	5.77	0.0053	0.0055	0.0047	0.0064
ϵ_{markup_m}	Uniform	10	5.77	0.0005	0.0005	0.0004	0.0006
ϵ_{markup_e}	Uniform	10	5.77	0.0004	0.0004	0.0003	0.0004
ϵ_{EC}	Uniform	10	5.77	0.0288	0.0295	0.0253	0.0341
ϵ_{ECAB}	Uniform	10	5.77	0.0379	0.038	0.029	0.0486
ϵ_{LTVH}	Uniform	10	5.77	0.1353	0.1563	0.1105	0.208
ϵ_{EbF}	Uniform	10	5.77	0.0423	0.0435	0.0369	0.0516
ρ_A	Beta	0.5	0.2	0.9956	0.9905	0.9786	0.9978
ρ_J	Beta	0.5	0.2	0.9849	0.9836	0.9733	0.9919
ρ_H	Beta	0.5	0.2	0.9572	0.9416	0.9051	0.9723
ρ_{Se}	Beta	0.5	0.2	0.499	0.4983	0.1723	0.8312
ρ_{SB}	Beta	0.5	0.2	0.0328	0.0498	0.0143	0.0984
ρ_{We}	Beta	0.5	0.2	0.8434	0.835	0.7663	0.8981
ρ_{markup_m}	Beta	0.5	0.2	0.8717	0.8685	0.7839	0.9447
ρ_{markup_e}	Beta	0.5	0.2	0.9347	0.9304	0.8851	0.969
ρ_{EC}	Beta	0.5	0.2	0.8424	0.8433	0.8012	0.8787
ρ_{ECAB}	Beta	0.5	0.2	0.9268	0.9194	0.8675	0.9678
ρ_{LTVH}	Beta	0.5	0.2	0.9292	0.9082	0.8207	0.971
ρ_{Wb}	Beta	0.5	0.2	0.9733	0.9587	0.9008	0.9907
ψ_i	Normal	4	1.5	7.9159	8.0655	5.7808	10.5123
ψ_h	Normal	4	1.5	4.8532	5.821	3.5007	8.4709
ζ_m	Beta	0.5	0.2	0.7179	0.7155	0.6629	0.7607
ζ_e	Beta	0.5	0.2	0.4967	0.4914	0.4333	0.5468
β_m	Beta	0.98	0.01	0.9719	-	-	-
λ	Beta	0.5	0.2	0.6626	-	-	-
σ_e	Inv. Gamma	2	0.1	0.0802	-	-	-
σ_m	Inv. Gamma	2	0.1	0.0915	-	-	-
σ_B	Inv. Gamma	2	0.1	0.0751	-	-	-

Figure 3: Posterior distributions of estimated Calvo parameters on interest rate setting.



3.4 Estimated Shocks

Figure 4 shows some of the key estimated shocks along with their 95% HPD intervals[22] over our sample period, which illustrates which shocks play a dominant role during the financial crisis period. Accordingly, it takes the combination of several adverse shocks to generate the crisis in the model. On the housing side, the main drivers emerge as the housing preference and housing price shocks as both of them fall considerably around the crisis period[23]. The house price shock in our model plays a qualitatively similar role to a measurement error, i.e. it is an external shock that directly hits the house price level. Keeping everything else equal, the effect of such a drop in housing prices is to boost housing demand and investment. Therefore, the adverse effects of the house price drop on output growth and the macroeconomy as a whole are picked up by the housing preference shock. Similar to the housing shocks, there is a sizeable drop in the consumption preference shock, which slowly starts to pick up after the crisis but remains persistently low throughout the sample period. The drop in consumption preference helps explain the reduction in consumption growth and, as a result, in output growth. Given the similar patterns in housing and preference shocks, these two simultaneous drops can be interpreted as an increased risk aversion to spending by households[24].

On the business side, the entrepreneur and expected capital price shocks play a dominant role compared to the rest. The entrepreneur net worth shock decreases during the crisis but quickly picks up afterwards, while the expected capital price shock gradually decreases after the crisis. The entrepreneur net worth shock plays a particularly important role in driving output growth as we will discuss below. This shock has a redistributional effect from households to the corporate sector, and as such we interpret it as picking up the effects of an external government spending shock in our framework. It is important to note that this shock remains elevated during the post-crisis period compared to its values during early 2000s.

Finally, the productivity shock decreases during the crisis period. We observe a pattern in the productivity process similar to (but opposite of) the entrepreneur net worth shock, where the productivity process not does recover after the crisis period and remains lower compared

[22]The full set of shocks, along with all of the observable variables are reported in Appendix A.

[23]We tested alternative version of the model with depreciation and expected price shocks on the housing side, in which case the role played by the preference and house price shocks are somewhat reduced.

[24]Note that there is also a substitution effect at play with these two preference shocks: since both preference shocks leave the household wealth unchanged, a negative consumption preference shock increases housing demand whereas a negative housing preference shock increases consumption spending.

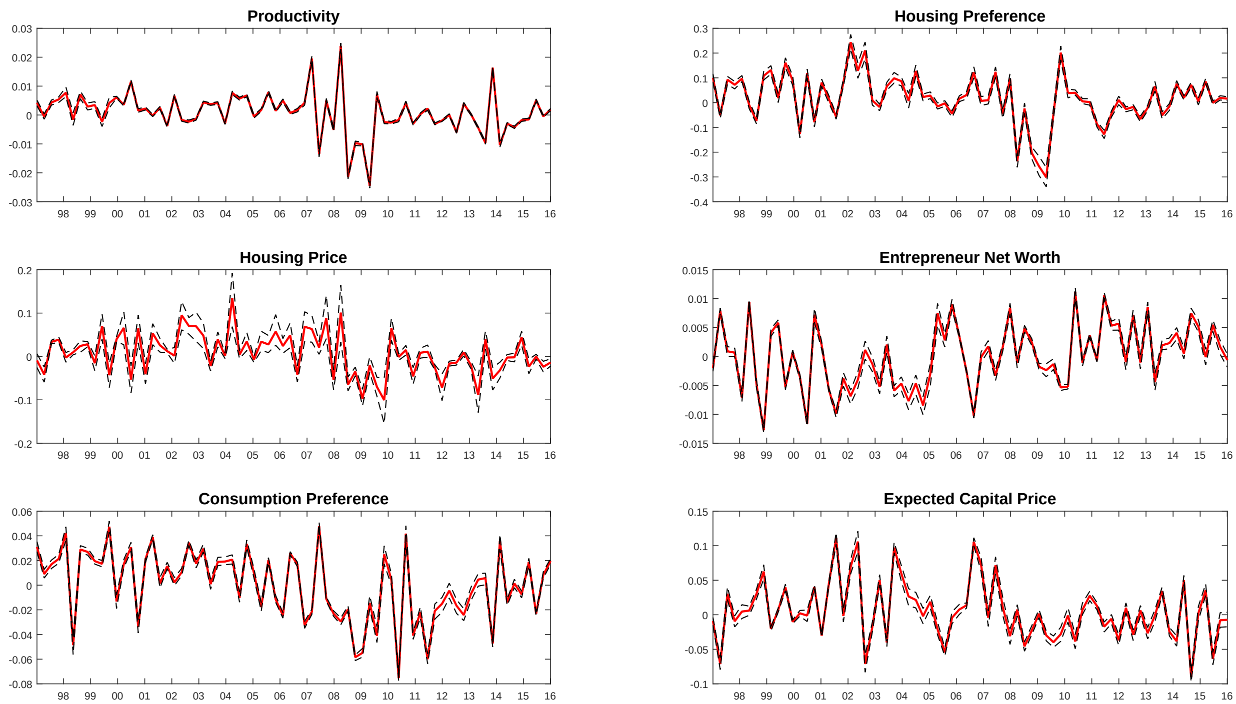
to its pre-crisis level. The post-crisis lower productivity is consistent with the conventional wisdom surrounding productivity in the U.K.

The remaining shocks (not reported in Figure 4) play a smaller degree during the crisis period and over the business cycle as a whole: the mortgage and corporate loan mark-up shocks are typically small with the exception of when interest rates fall to the zero lower bound levels. This corresponds to the period where the gap between the official bank rate and the mortgage and corporate loans grows. Accordingly, these two shocks help generate the interest rate stickiness and obtain the Calvo probabilities reported in the previous section. The bank net worth and bank capital shocks also play a surprisingly small role especially surrounding the crisis period. Finally the housing LTV shock decreases once the adverse shocks hit, which is interpreted as the borrowing constraint becoming more restrictive during this period. However, this shock does not play a substantial role in the variance decompositions as will be discussed below.

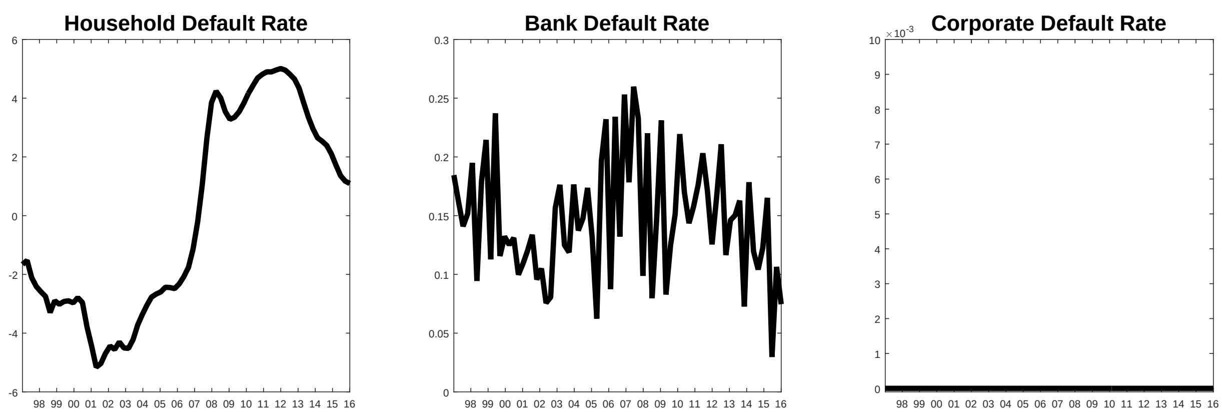
Figure 4b shows the estimated default rates across all three sectors. It is readily seen that corporate default rates remain practically at zero throughout the sample period, implying this layer of default does not play an important role. The bank default rate is somewhat increased during the crisis period, although it still remains at low levels throughout the sample[25]. Unlike the bank and corporate default rates, the household default rate is substantially increased during the crisis period, and it remains elevated until 2012 before starting to come down. Together with the redistributional entrepreneur net worth shock, this increase in the default rate can be interpreted as households bearing most of the cost of the crisis in our model.

[25] We experimented with an alternative version of the model, where we use the average price-to-book ratio of U.K. banks as a proxy for the AR(1) bank risk shock, which directly determines the bank default rate in the model. In this case we obtain a sharper jump in the bank default rate during the crisis, but the overall default rate as well as the wider implications for the model remain qualitatively the same.

Figure 4: Estimated Shocks and Default Rates over 1998Q1-2016Q2.



(a) Key shocks driving the financial crisis in the model.



(b) Default rates during the sample period, where y-axis shows the deviation in percentages from steady-state.

3.5 Variance Decompositions

We next turn to variance decompositions of some key variables in order to see how the estimated shocks as discussed above transmit through the economy during the sample period. We focus on two variables in particular, namely the mortgage lending and output growth rates, which are shown in Figure 5 . The unconditional decompositions of some other observable variables is also reported in Table 3, which will be discussed further below.

Starting with the mortgage lending growth rate, it is readily seen that the main drivers are housing preference and house price shocks as previously discussed. The external drop in house prices has a ceteris paribus effect of increasing housing demand and therefore demand for housing loans. Therefore the house price shocks contribute negatively to the mortgage lending growth during the pre-crisis period when house prices are increasing, and negatively during the post-crisis period when the housing price trend reverses. Given the house price shocks, the housing preference shocks are large enough to generate positive growth before the crisis, and negative growth after the crisis. Aside from these shocks, bank capital and consumption preference shocks also play an smaller but non-negligible role in terms of driving mortgage lending growth.

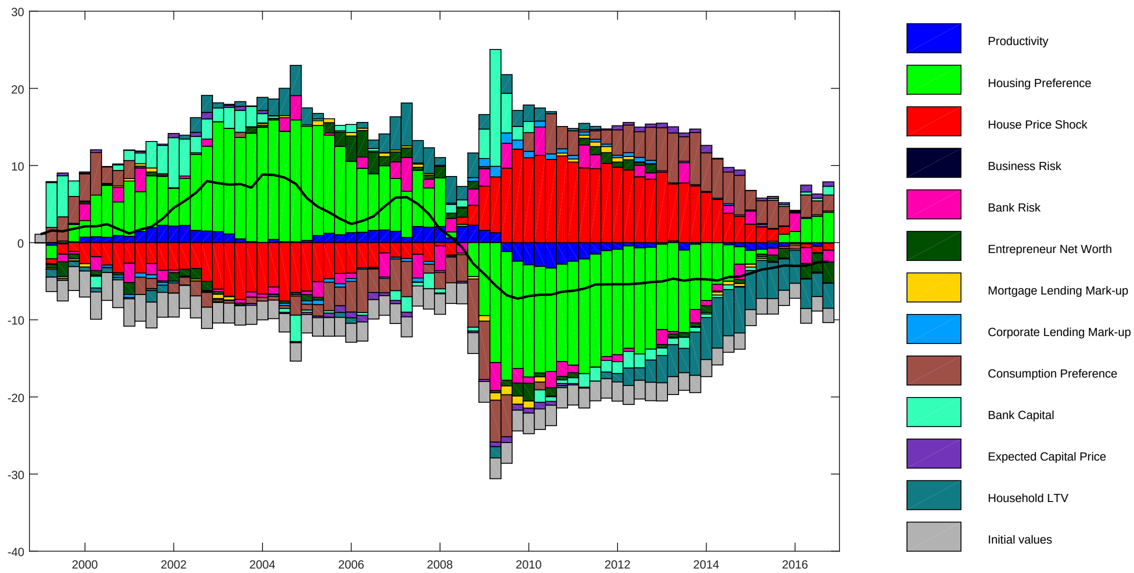
Next looking at output growth, we observe that several shocks emerge as important drivers, namely the productivity, entrepreneur net worth and consumption preference shocks. The housing preference shock also plays a role to a smaller extent, and the house price shock becomes particularly important with the onset of the crisis. During the crisis period, all four of these shocks contribute negatively to output growth, whereas bank capital and house price shocks contribute positively. Interestingly, the productivity shock contributes positively throughout the early 2000s until the crisis, while it contributes negatively for a long period after the crisis until mid-2015. The contributions from consumption preference turn positive shortly after the crisis, while the negative ones from housing preference persists. The entrepreneur net worth shock, while playing a relatively large role overall, has periods of both positive and negative contributions both before and after the crisis. Accordingly, the low output growth rate post-crisis is explained by productivity and housing preference shocks, and to some extent the entrepreneur net worth shocks. The positive contribution from house price shocks during the crisis period works through the channel of boosting housing demand and investment. Therefore we interpret this shock on output growth as picking up the effects of a looser monetary policy, which would work through the same channel of boosting demand and investment.

Table 3 shows the unconditional decompositions of output and mortgage lending growth rates, along with the other growth rates used as observables in the estimation. It is readily seen that, as discussed above, the output growth rate is mainly dominated by productivity, consumption preference and entrepreneur net worth shocks. The role for both housing shocks are substantially reduced compared to the historical decomposition, which is intuitive since these shocks affect output growth mostly during the period surrounding the crisis. Similarly, the housing preference and housing price shocks are the dominant drivers both for house price and mortgage lending growth rates[26]

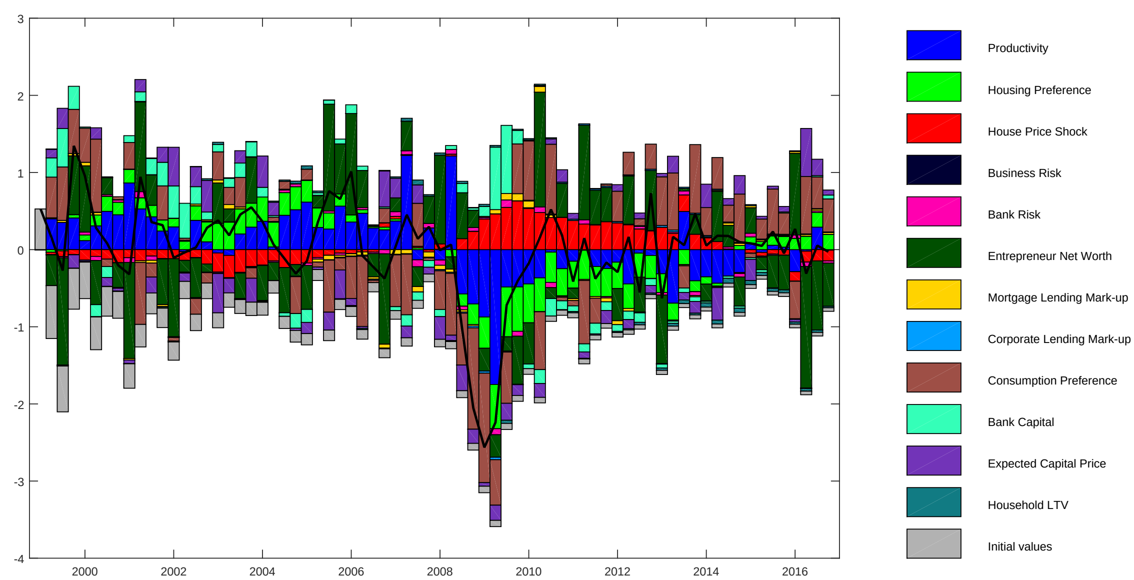
For corporate lending growth rate, the expected capital price and entrepreneur net worth shocks are the dominant players as expected, while wage growth rate is mainly driven by productivity shocks. Finally, the consumption growth rate is mainly dominated by productivity and consumption preference shocks, which is similar to the output growth rate with the exception that the role of the entrepreneur net worth shock is absorbed by preference shocks.

[26]For lending growth rates, the bank capital shock also plays an important role, making up around 25 % of the fluctuations for both variables. Hence the contribution from the *other shocks* category mainly consists of the bank capital shock for these variables, while the *other shocks* category does not play a substantial role for the other variables.

Figure 5: Historical variance decompositions of mortgage lending and output growth rates.



(a) Mortgage lending growth rate.



(b) Output growth rate.

Table 3: Unconditional variance decompositions of key variables. The variables we consider are output growth Δy_t , house price growth Δq_t^H, corporate lending growth Δb_t^e, mortgage lending growth Δb_t^m, wage growth Δw_t, and consumption growth Δc_t .

Shocks	Δy_t	Δq_t^H	Δb_t^e	Δb_t^m	Δw_t	Δc_t
Productivity	17.58	0.85	12.26	1.78	88.53	21.07
Housing Preference	2.01	59.65	2	37.63	0.45	4.81
Housing Price	1.66	33.35	1.9	10.81	0.73	4.1
Entr. Net Worth	33.45	0.18	16.57	1.66	0.62	0.55
Consumption Pref.	31.65	4.49	1.08	11.33	7.58	66.21
Exp. Capital Price	3.63	0.07	39.8	0.28	0.28	0.19
Other	10.02	1.41	26.39	36.51	1.81	3.07

4 Macroprudential Policy & Welfare Analysis

In this section we analyze the effects of macroprudential policy tools on aggregate household welfare, output and credit. We discuss the effects of macroprudential tools in two steps. First, we analyze the steady-state of the model, abstracting away from any business cycle fluctuations. Using this approach, we find the welfare-maximizing macroprudential policies individually and jointly. This allows us to discuss whether the right combination of macroprudential tools can be welfare improving. Second, using the optimal policies from our steady-state analysis, we discuss a number of counterfactuals to see what effect the macroprudential policies would have had on the economy if they had been in place before the crisis.

4.1 Optimal Policy at the Steady State

To assess the effects of macroprudential policies, we start by defining household welfare as follows:

$$W_t = \frac{W_t^s C_t^s + W_t^m C_t^m}{C_t^s + C_t^m}$$

where W_t^i and C_t^i with $i \in \{s, m\}$ refer to the welfare and consumption of patient and impatient households respectively. Accordingly, our welfare measure is a weighted average of patient and impatient households, where the weights are determined by the consumption shares of households[27]. Given this definition of aggregate welfare W_t, we use a standard liner-quadratic function as our objective:

$$E[W_t] - \omega\sqrt{Var[W_t]}.$$

Our motivation to include the welfare volatility in our objective function is to capture potential second-order effects of macroprudential policies, since our model is based on a first-order approximation. We consider two cases for the weight on volatility: (i) with $\omega = 0$, which focuses on the expected welfare and ignores these potential second-order effects, and (ii)

[27]This definition of welfare closely follows from Mendicino et. al. (2018).

$\omega = 0.1$, which shows us the effects of including the welfare volatility on the resulting optimal policies.

We first find the optimal values of macroprudential tools when they are used individually. To this end, we use a grid search for each policy tool under consideration, where the other tools remain fixed at their baseline level[28]. The results are reported in Table 4. When $\omega = 0$ (no weight on welfare volatility), we find that the optimal LTV is looser at 89.4% compared to its baseline level of 86%, and it comes with a marginal improvement on welfare with 0.014%[29]. For the sectoral capital requirements (SCRs), we find relatively large optimal values (compared to the baseline of 11%) of 20.7% and 15.5% for mortgage and corporate rates respectively, while the optimal CAR turns out to be 15.5%. The welfare improvement among the three is largest when maximizing over mortgage SCR with 7.47%, and smallest when maximizing over corporate SCR with 15.5%. As such, our results suggest that sectoral SCRs on mortgage lending is more important than those of corporate lending from a household welfare perspective. When we also place some weight on welfare volatility with $\omega = 0.1$, we observe that the optimal LTV becomes tighter compared to $\omega = 0$ and it remains very close to its benchmark value of 86%. Further, for both SCRs and CAR, we find smaller optimal values compared to $\omega = 0$ case, suggesting a trade-off between welfare level and welfare volatility. Nevertheless, these results indicate that there is a well-defined optimal policy in terms of LTVs, SCRs and the CAR. As an illustration, Figure 6 shows this result with respect to housing SCR and CAR: it is readily seen that the expected aggregate welfare attains a maximum at the optimal values specified in Table 4[30].

We also include optimal policy implications on CCyB in Table 4 for comparisons.

Finally note the results on optimal CCyB, which follow mechanically: since the CCyB reacts to fluctuations of corporate and mortgage lending rates over the business cycle, it does not affect the steady-state levels of lending rates or welfare (i.e. the expected values of lending rates and welfare). Therefore, when there is no weight on welfare volatility, no optimal CCyB exists. At the other extreme, CCyB always reduces the volatility of lending rates and therefore volatility of welfare. Hence for any $\omega > 0$, the optimal CCyB is to simply set it as high as possible.

Given the individual optimal policies, we next investigate whether coordinating these policies (i.e. optimizing them jointly) may lead to further welfare improvements[31]. Table 5 reports the joint optimal combination of LTV, CAR and SCRs for the same cases with $\omega = 0$ and $\omega = 0.1$[32,33]. With no weight on volatility, we find that optimal LTV is looser compared to the previous case, with 91.25% (compared to 89.4 %), mortgage SCR is higher with 21.25% (compared to 20.7 %), and corporate SCR reduces to its lower boundary of 5% (which also implies a CAR of 5%). This scheme puts an excessive weight on mortgage lending requirements

[28] For each tool, we use a grid length of 100. For housing LTV, we consider the range over $[0.7, 0.95]$, while for SCRs and CARs, the range is $[0.05, 0.25]$. For certain policy combinations with SCRs below 0.05 and LTV below 0.7, we encounter indeterminacy. As such, the policy ranges are that we use are determined approximately by the indeterminacy boundaries.

[29] Recall that the LTV limit in our model is assumed to be an always binding constraint. Our results on LTV here may be sensitive to the formulation of this, but we leave the occasionally binding LTV to future research.

[30] The figures for welfare volatility, as well as for the LTV limit and corporate SCR are omitted here for brevity, but similar results follow.

[31] CCyB is excluded from this exercise since, as reported in Table 4, it does not affect the steady-state welfare level.

[32] For this exercise, we use a smaller grid size of 20 since the dimension of the problem is larger.

[33] Note that we effectively maximize over three policies, i.e. LTV and SCRs. The CAR is implicitly determined as the minimum of the two SCRs.

Table 4: Maximizing over prudential policy parameters, one at a time. LTV refers only to housing loan-to-value limit in this case, and we leave the corporate LTV at its baseline level of 86 % throughout. The baseline policies are LTV= 86%, and CAR= 11% (i.e. both SCRs are set to 11%). The numbers in parathesis indicate the improvement in aggregate welfare relative to the baseline.

	ω	0	0.1
Parameter			
LTV		89.4 % (0.014 %)	86.6 % (0.001 %)
SCR-Mortgage		20.7 % (7.47 %)	17.6 % (4.26 %)
SCR-Corporate		15.5 % (3.33 %)	16.7 % (3.22 %)
CAR		15.5 % (5.11 %)	14.5 % (3.82 %)
CCyB		NaN	Max. allowed

and as can be readily seen from Table 5, it leads to a larger welfare improvement of 8.01 %, compared with improvements ranging over $[0.014, 7.47]$ at individual optimal policies.

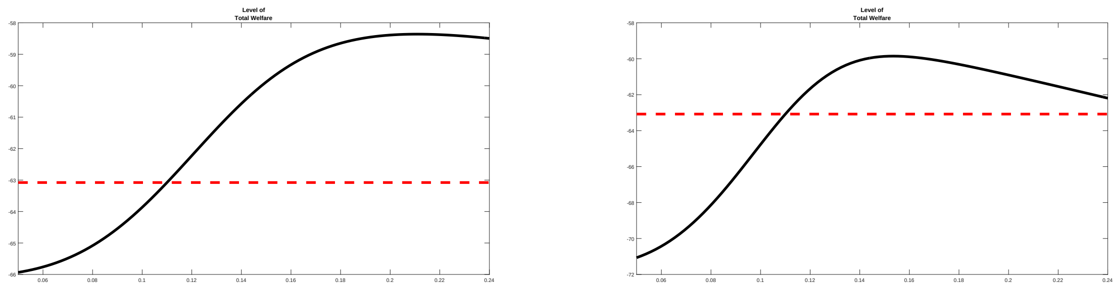
With some weight on welfare volatility, i.e. $\omega = 0.1$, we find that optimal LTV is even looser with 94%, while sectoral SCRs are now at closer levels with 15.88% and 12.5% on mortgage and corporate lending respectively (and CAR is 12.5%). This suggests that the excessively lost SCR on corporate lending in the previous case comes at a cost of higher volatility, and therefore introducing some weight on volatility increases the optimal corporate SCR to a more reasonable level. The welfare improvement in this case turns out to be 4.8%, which is again larger than the improvements obtained by individual optimal policies ranging at [0.001.4.26]. This establishes our key result for this section: the appropriate combination of macroprudential tools achieves a better welfare improvement compared to when the tools are used individually.

Using these results, we next run a set of counterfactuals to analyze whether the macroprudential tools also achieve a better outcome over the business cycle.

Table 5: Maximizing over SCRs and LTV at the same time

	ω	0	0.1
Parameter			
LTV		91.25 %	94.06 %
SCR-Mortgage		21.25 %	15.88 %
SCR-Corporate		5(Min. attainable) %	12.50 %
Welfare Improvement		8.01 %	4.8 %

Figure 6: Sectoral capital requirements on mortgage lending with a baseline of 11 %. Welfare maximizing value is 20.7 % with a weight of 0 on volatility. It decreases to 17.6 % with a weight of 0.1 on the volatility. **Welfare improvement: 7.47 % and 4.26 % respectively.**



(a) Welfare level as a function of housing SCR.

(b) Welfare level as a function of CAR.

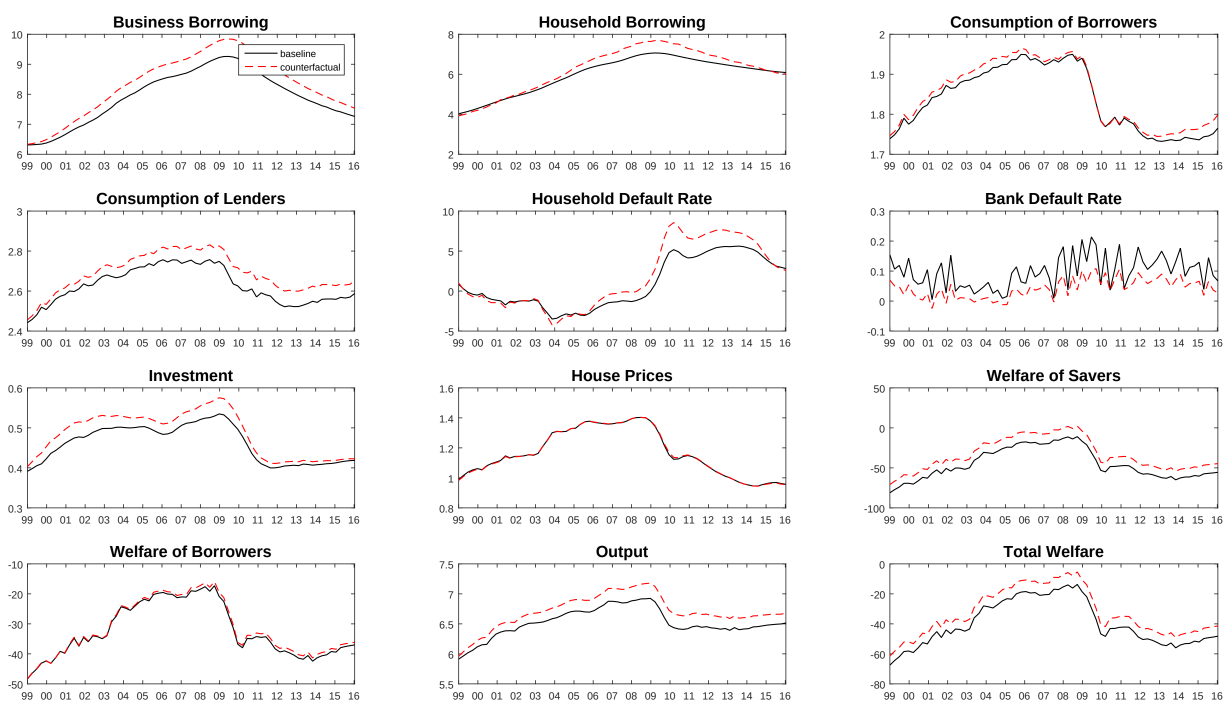
4.2 Counterfactual Simulations

In this section we analyze what would have happened if different macroprudential tools were in place before the financial crisis through the lense of our model. To this end, we use the joint optimal policies with $\omega = 0.1$, hence we set the LTv limit to 94%, housing SCR to 15.8% and corporate SCR to 12.5%. We use the parameters at the estimated posterior mode as reported in 2 and run several counterfactual simulations as follows: we use the smoothed shocks implied by the estimated parameter values, and the shocks remain fixed at these benchmark values. We then re-simulate the economy, where the system is subject to the same set of shocks but different macroprudential policies (i.e. the optimal ones that we found) are in place prior to the crisis.

In our first exercise, we assume that the optimal policies are always in place from the beginning of the sample. The patterns of some key variables under the baseline and counterfactual scenarios are reported in Figure 7. As the values of optimal policies make it clear, the optimal macroprudential that we found prescribes a looser borrowing constraint through a higher LTV limit (compared to the benchmark scenario), and a more resiliant bank through higher SCRs (and therefore CAR). This is exactly the result that comes out of our counterfactual simulation: due to higher capital requirements, the bank default rate decreases compared to the benchmark scenario. The higher housing SCR and looser LTV limit have opposing effects on household borrowing, and looking at the figure we observe that the looser LTV limit somewhat dominates, resulting in a higher household borrowing. While the corporate SCR is higher compared to the benchmark scenario, the relative increase is smaller compared to the housing SCR. This leads to a substitution effect on the bank's side, where the bank prefers to shift its portfolio from mortgage lending to corporate lending. It is readily seen that this substitution effect dominates the increase in the absolute level of corporate SCR (from 11 % to 12.5 %), and the business borrowing ends up higher under the counterfactual scenario compared to the baseline. The increased borrowing also boosts housing and capital investment, which feeds back into the consumption of both impatient (borrower) and patient (lender) households, as well as the aggregate output. The default rate of households increases under the counterfactual since the amount of borrowing is higher, but the disutility of this increased default rate is mostly offset by the utility of increased consumption and a lower bank default rate (which has a cost on the households). Therefore the borrowers are almost equally well-off under the counterfactual, while the lenders are better off due to increased consumption and investment. This results in a higher output and total welfare under our counterfactual scenario, even though the drops associated with the crisis are at similar levels compared to the baseline scenario. Accordingly, a looser borrowing limit combined with a more resilient bank results in an overall beneficial outcome.

Looking at the percentage changes for our target variables in Figure 7, it is readily seen that, the average volumes of lending, as well as aggregate output and welfare are all higher under the counterfactual scenario. However, a similar level of drop after the financial crisis is still present in all variables. This suggests that, if different counterfactual policies were in place before the crisis, some aggregate indicators would have been improved but the crisis would not be prevented altogether. This is consistent with the policy of a looser borrowing constraint and a more resilient banking system, which does not aim at preventing the crisis but rather makes the system more resistant to it[34].

Figure 7: Counterfactual I: using optimized values with 0.1 weight on volatility. $\phi_H = 15.8\%, \phi_F = 12.5\%, \epsilon_H = 94\%$. For target variables, the average increases over the sample period are 4.9 % for corporate credits, 4.2 % for mortgage credits, 2.8 % for output and 17.6 % for households welfare.

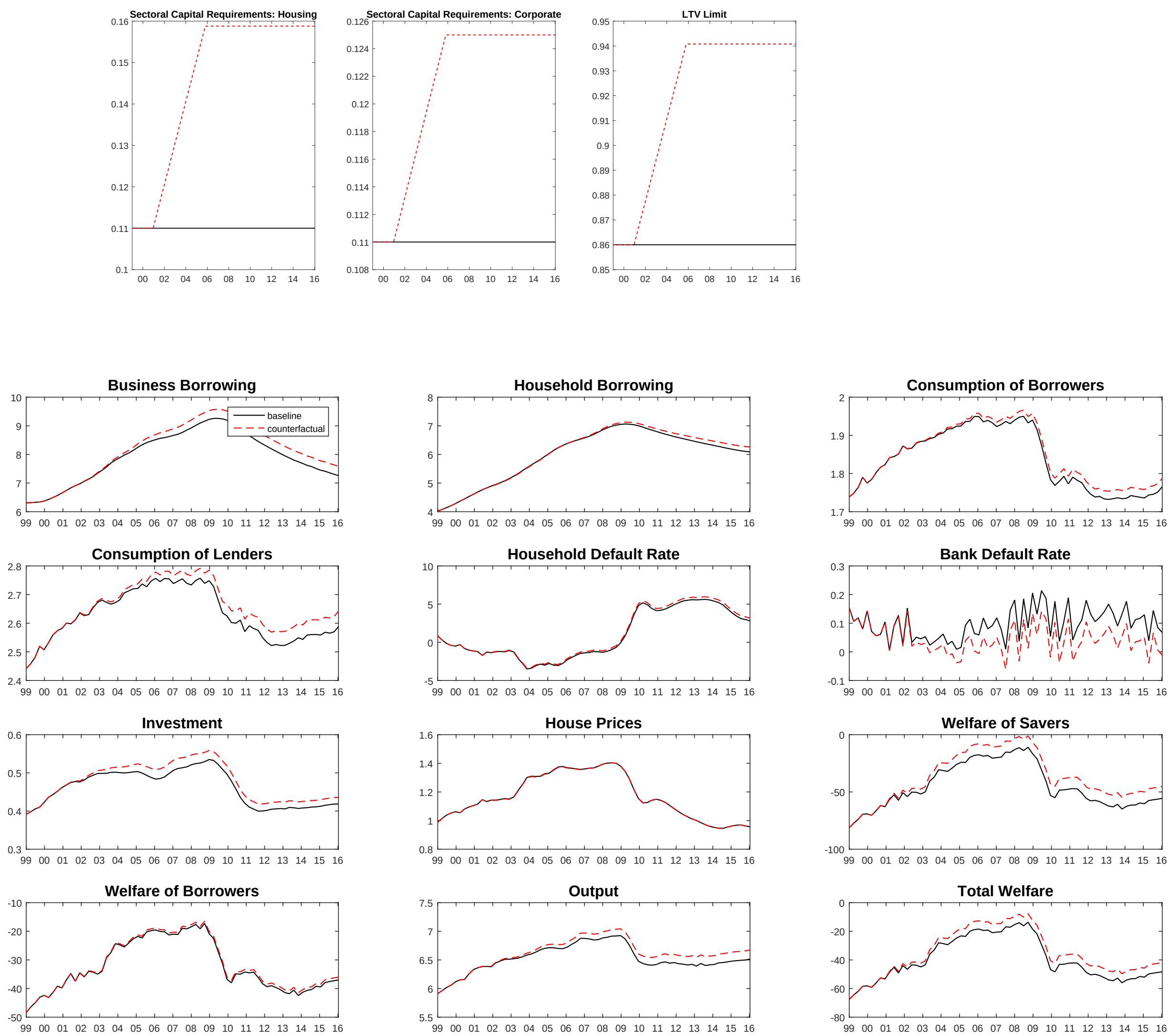


Next we consider a more realistic alternative scenario, where the same optimal policies are introduced over a 5-year period between 2001 and 2006. In this case we start from the

[34]An alternative policy analysis would involve the optimal scenario under a counterfactual simulation that finds the right balance between the level and volatility. This is omitted in our paper.

benchmark policies in the year of 2001, and we gradually phase-in the policies until they reach the optimal levels over the 5-year period[35]. As might be expected, we obtain the same (positive) direction in all target variables both in terms of level and volatility, but the resulting magnitudes are substantially smaller since the policies are in place for a shorter duration. In both cases with and without phasing in, we obtain a welfare improving outcome under the optimal policy scenarios.

Figure 8: Same counterfactual phased-in over a 5-year period over 2001-2006 in equal increments. For target variables, average increases over the sample period are 2.4 % for corporate credits, 0.8 % for mortgage credits, 1.3 % for output and 11.4 % for household welfare.



Finally, to investigate the effects of CCyB at the business cycle frequency, we analyze what

[35]For this exercise, we introduce unit root shocks into the model on SCRs and the LTV limit. The policies are then phased-in in the form of permanent shocks.

happens with the introduction of CCyB when the optimal LTV and SCRs are already in place. To this end, we consider three scenarios with (i) a CCyB on corporate lending, (ii)CCyB on mortgage lending, (iii) CcyB in both sectors. Given our policy function, CCyB reacts to deviations of corporate and mortgage lending from its steady state level. We set the CCyB level to generate a standard deviation of approximately 2.5 % in minimum requirements, which is obtained by tuning the reaction parameters in the policy function[36]. The results are reported in Table 6: we observe that introducing CCyB when the other optimal policies are already in place improves the outcomes further in terms of levels. In particular, aggregate output and welfare levels are improved when CCyB is active in both sectors, as well as when it is active in each sector individually. However, it is worth noting a downside with using CCyB in this form: during the sample period, the mortgage and corporate borrowing rates continue increasing above their steady-state levels during the pre-crisis period, and while they start declining with the onset of the crisis, they are still well above their steady-state values once the crisis hits, and they remain above that level throughout the whole sample. As such, a CCyB that reacts to deviations of borrowing rates from their steady-state level prescribes ever-increasing capital requirements throughout the sample period. This issue may exaggerate and bias the impact of CCyB[37].

Table 6: Does CCyB improve things when optimal SCRs are in place?

Variable	% Change in Level	Variable	% Change in Level
Baseline optimal SCR+LTV		CCyB 2.5 %, mortgages	
Corporate Credit	4.9	Corporate Credit	7.3
Mortgage Credit	4.2	Mortgage Credit	0.05
Output	2.8	Output	3.9
Household Welfare	17.6	Household Welfare	19.4
CCyB 2.5 %, both sectors		CCyB 2.5 %, corporate	
Corporate Credit	5.8	Corporate Credit	3.2
Mortgage Credit	4.5	Mortgage Credit	8.1
Output	4.1	Output	2.7
Household Welfare	21.2	Household Welfare	19.1

5 Impulse Response Analysis

5.1 Interest Rate Stickiness and Shock Propagation

In this section we discuss the effects of individual shocks on key variables through impulse response functions. We first start with the effects of interest rate stickiness on shock propagation. Given the significant rate of stickiness on U.K. data, this can be an important channel that affects the transmission of shocks throughout the economy. We focus on three shocks across different sectors of the economy, namely a housing preference shock on the housing side, an

[36]This results in a parameter value of 0.051 that reacts to deviations of mortgage lending from its steady state, and a parameter value of 0.128 for corporate lending.

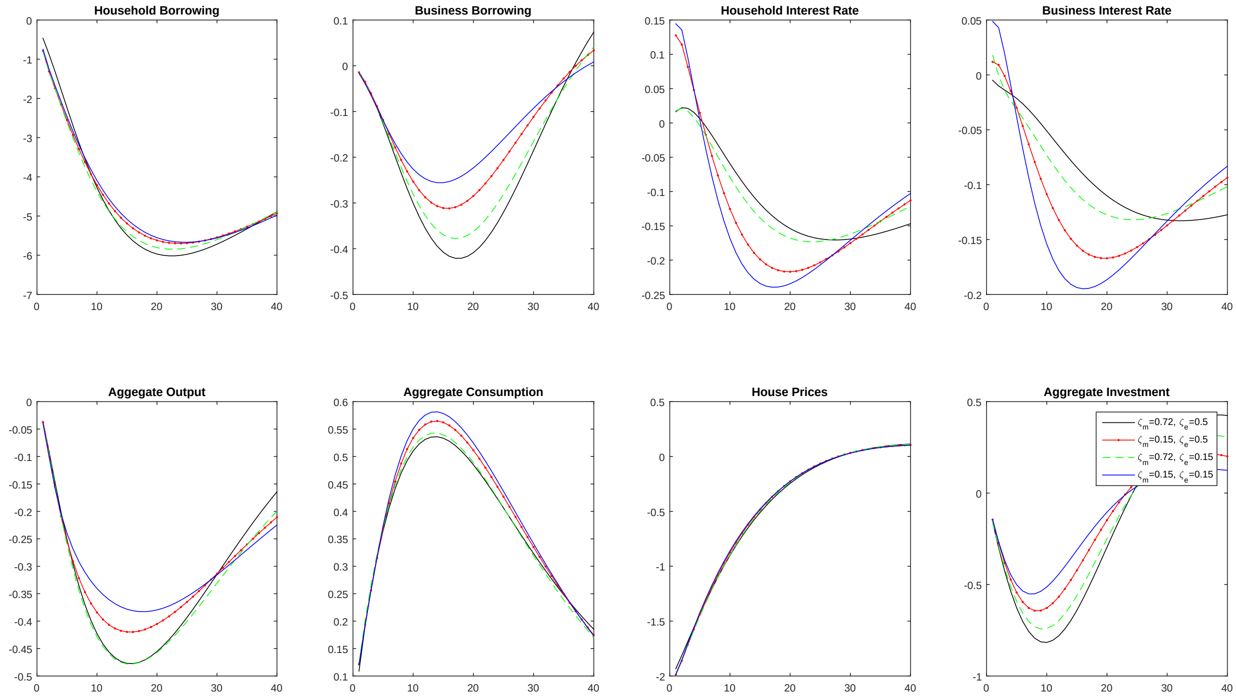
[37]Alternative reaction functions such as a CCyB on the growth rate of lending rates could resolve the issue, which we to future research.

expected capital price shock on the corporate side and a bank capital shock on the banking side. We report the effects on several key variables with and without interest rate stickiness in each sector. In particular we focus on four scenarios in terms of interest rate stickiness: (i) estimated degrees of stickiness, (ii) a low degree of stickiness in the housing sector, (iii) a low degree of stickiness in the corporate sector and (iv) a low of degree stickiness in both sectors[38].

Figure 9 reports the effects of a negative housing preference shock: the shock directly lowers the demand for borrowing by households, which translates into a drop in house prices. Since the shock leaves the level of household wealth unchanged, they increase their consumption spending. The effects on these three variables are similar with different degrees of stickiness, since the shock originates in the household sector and does not transmit through interest rates. In response to the drop in housing demand, the bank lowers the household interest rate and this is where we start to see the effects of interest rate stickiness: it is able to cut the interest rates the most when interest rate stickiness is low in both sectors, while the drop in interest rates is smallest when the stickiness is at the estimated level in both sectors. In response to the drop in house prices, aggregate investment (which consists of housing and capital investment) also decreases subject to a similar constraint as the housing sector depending on the degree of stickiness. Similar to the household interest rates, the bank also ends up lowering corporate rates for two reasons: first, keeping the corporate rates constant while lowering mortgage rates would result in a substitution effect into the housing sector in terms of credit demand, and therefore the bank has an inventive cut corporate rates in response to mortgage rates. Second, the volume of business borrowing decreases given the lower aggregate investment, and therefore the bank prefers lower business lending rates to make up for the loss in demand. The net effect on aggregate output in general depends on the positive effects on aggregate consumption and the negative effects on aggregate investment. Under our parameterization, the negative effects dominate and we see a reduction in aggregate output following the housing preference shock. The effect is smallest when the degree is stickiness is small in both sectors, and the stickiness in mortgage rates has the highest impact on aggregate output in this case. This is intuitive since the shock starts from the housing sector, and hence the largest spillover effect takes place when the bank is unable to cushion the shock through mortgage rates.

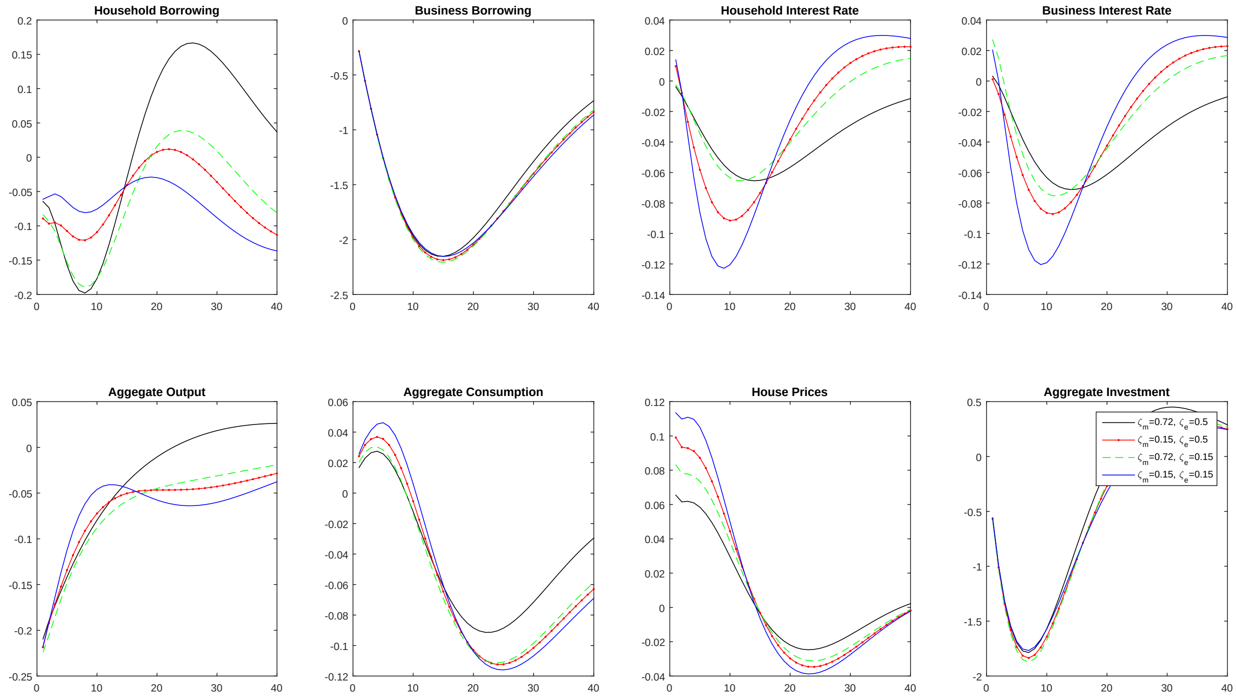
[38]We use a stickiness rate of 15 % in the low stickiness scenarios, lower values lead to indeterminacy.

Figure 9: Impulse responses to a negative housing preference shock.



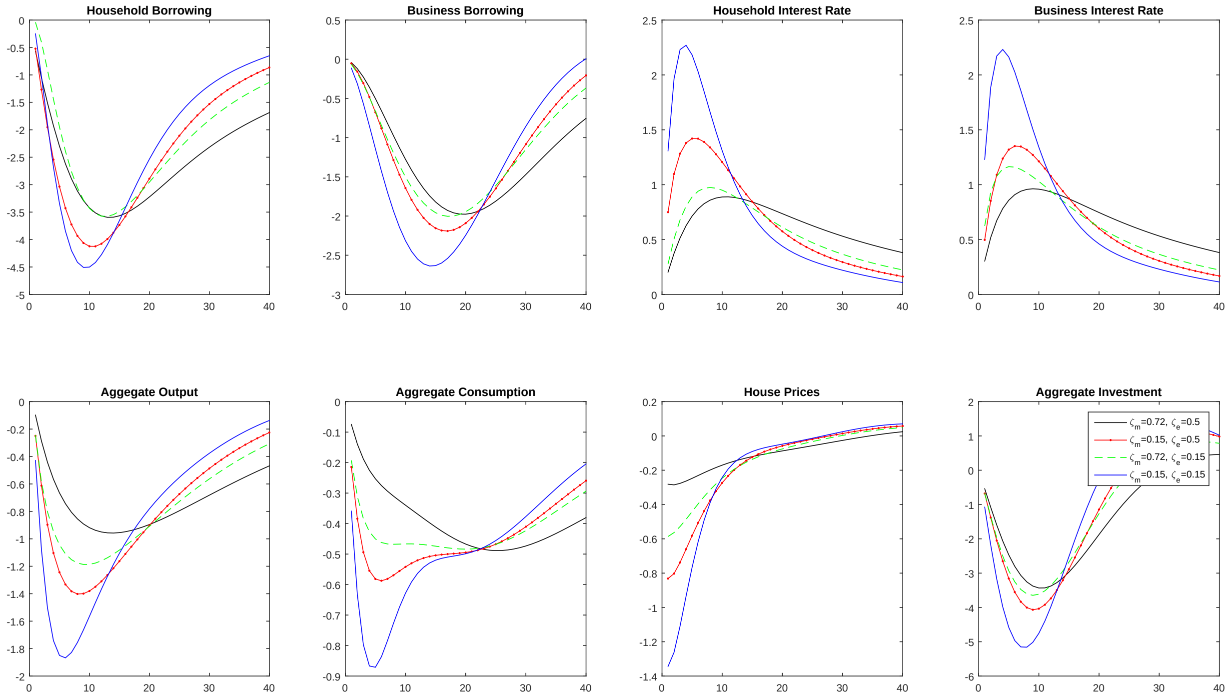
Next we turn to Figure 10, which reports the effects of a negative capital price shock. Since the shock originates in the corporate sector, the immediate effects take place on the borrowing volume of businesses and aggregate investment: these variables decrease in all cases independent of the degree of stickiness. This effect spreads through two channels: first, the lower capital investment results in a substitution effect towards housing investment, which pushes up the house prices. As a result, households shift some of their spending from housing to consumption in the short run, which results in a higher consumption and lower household borrowing. As a response to lower volume of household borrowing, and to prevent the substitution effect from lower corporate rates, the bank cuts the housing lending rates. In the medium run after around 10 quarters, the effects of lower household lending rates start to kick in and the households start shifting away from consumption back into housing. The largest fluctuations in household borrowing takes place when both interest rates are at their estimated value (i.e. when they are stickiest). Interestingly, the stickiness rate in mortgage lending again plays a more important role than corporate lending, even though the shock originates in the corporate sector. The overall effects on output are only marginally affected by interest rate stickiness in this case, since the drop in investment is substantially larger than the short-term increases in consumption, which means the largest effect (through investment) does not transmit through interest rates.

Figure 10: Impulse responses to a negative expected capital price shock.



Finally we discuss the effects of a negative bank capital shock, which is reported in Figure 11. In this case the shock originates as a lower bank capital, to which the bank responds by increasing the lending rates in both sectors since it is not able to lend out as much. This unambiguously transmits through the rest of the economy in a negative manner, where the interest rates increase depending on the degree of stickiness (largest increase when stickiness is lowest). This results in lower borrowing volumes in both sectors. Investment and house prices both go down in response to the higher borrowing rates. In terms of consumption, there are again two effects: the lower household borrowing results in a substitution effect in households' spending bundle, but at the same time the lower aggregate investment results in a lower household wealth. It is clear from the figure that the latter effect dominates and household consumption goes down, which also results in a lower aggregate output. Unlike the previous two cases, we see the largest effects on output when interest rate stickiness is lowest. In the previous cases, the bank reacts through interest rates by trying to mitigate the adverse effects of shocks in other sectors, hence the effects are strongest when interest rates are stickiest. In this case, the bank reacts by trying to shift the adverse effects from itself onto households and businesses, and therefore the effect turns out strongest when interest rates are the least sticky.

Figure 11: Impulse responses to a negative bank capital shock.



5.2 Interest Rate Stickiness and Sectoral Capital Requirements

Given the importance of interest rate stickiness on the transmission of shocks, in this section we analyze how interest rate stickiness affects the impact of macroprudential policies. We focus on the policies that transmit through interest rates in our model, namely sectoral capital requirements and sectoral countercyclical buffers. In this case we focus on the response on lending volumes to a (positive) bank capital shock only, although the analysis can be extended to other shocks as well.

Figures 12 and 13 report the effects of low (11%) and high (15%) SCRs on corporate and mortgage lending respectively. Two important observations stand out from the figures: first, increasing SCRs in either sector generally lowers the lending volume in both sectors. Second, the difference between impulse responses under high and low SCRs is generally larger when interest rate stickiness is lower (i.e. the difference between green and blue curves tends to be larger than the difference between red and black curves). This suggests that a high degree of interest rate stickiness may weaken the effect of minimum capital requirements.

Figure 12: The impact of corporate SCR on lending volumes with high and low levels of interest rate stickiness.

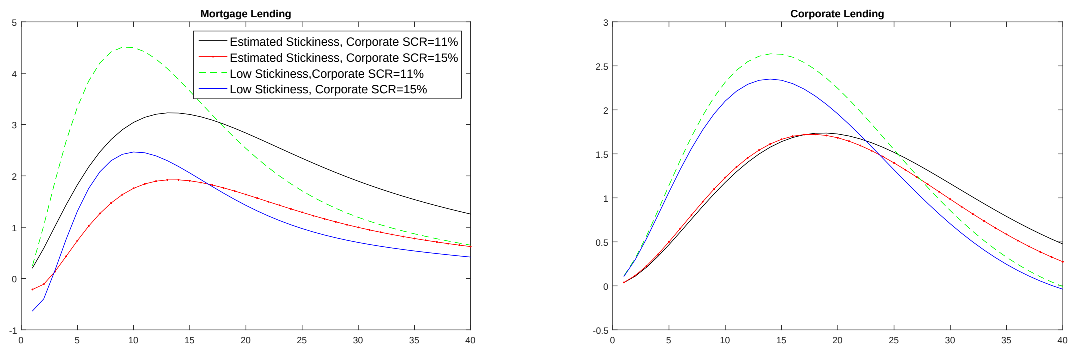
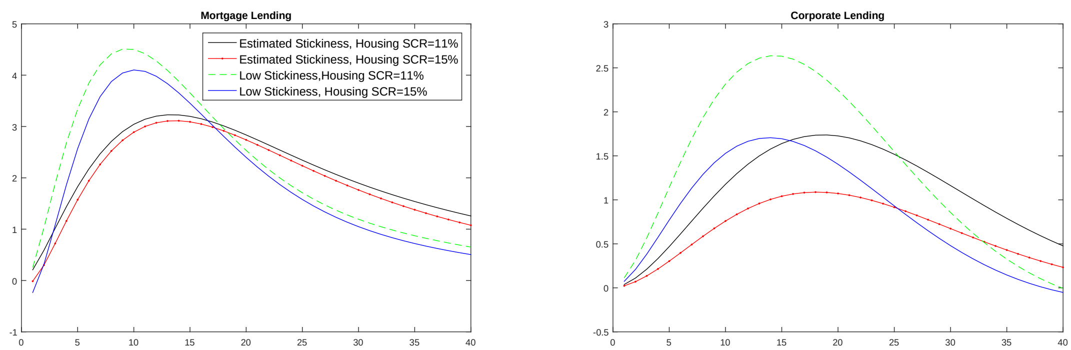


Figure 13: The impact of housing SCR on lending volumes with high and low levels of interest rate stickiness.



Similarly, Figures 14 and 15 report the effects of no sectoral CCyB and a 2.5% sectoral CCyB on housing and corporate lending respectively[39]. We observe in this case that, in both sectors, introducing a sectoral CCyB lowers the lending volume in that sector. However, there are two important differences compared to the SCRs: first, the differences with and without interest rate stickiness are smaller compared to the SCRs. Second, unlike the SCRs, we observe a substitution effect towards the other sector in this case: a sectoral CCyB in corporate lending increases the volumne of mortgage lending, and similarly a sectoral CCyB in mortgage lending increases the volume of corporate lending. These results emerge due to the gradual nature of CCyBs: since the tool builds up slowly over time, interest rate stickiness has a much smaller impact and the graduality allows the bank some time to substitute its lending volume towards the other sector.

[39]Similar to the previous section, the 2.5 % CCyB is obtained by tuning the parameter in reaction functions to generate a standard deviation of 2.5% in the capital requirement rates.

Figure 14: The impact of a 2.5 % corporate CCyB on lending volumes with high and low levels of interest rate stickiness.

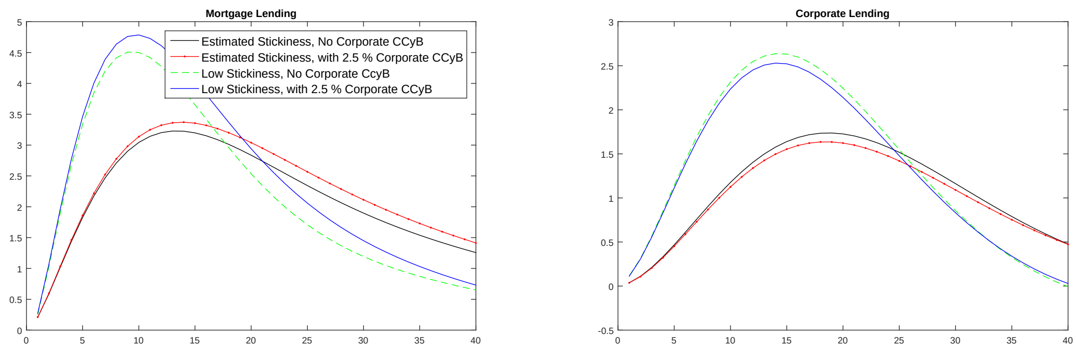
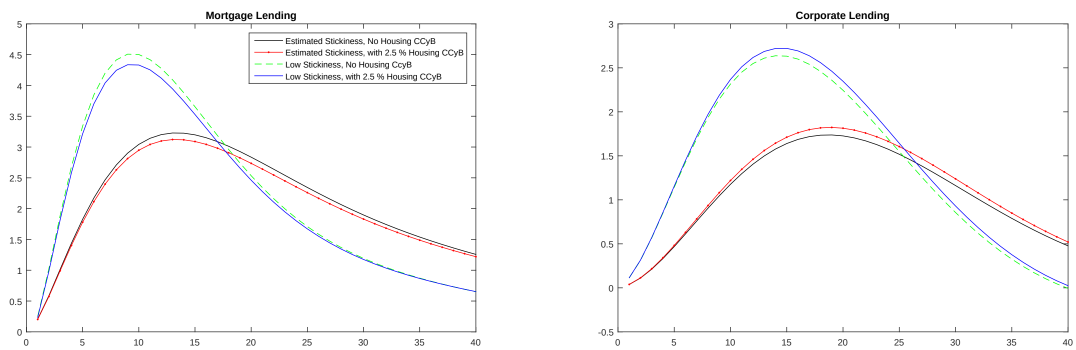


Figure 15: The impact of a 2.5 % housing CCyB on lending volumes with high and low levels of interest rate stickiness.



Overall, these results suggest that interest rate stickiness plays an important role both in terms of the transmission of shocks through the economy, and also in terms of the effectiveness of macroprudential tools that work through interest rates. This presents a new, important channel for the design of macroprudential policies and particularly for tools that affect the degree of interest rate stickiness through long-term contracts.

6 Conclusion

Assessing the effectiveness of the macroprudential toolkit is essential for ensuring that that the risk of future financial crises is reduced to the largest degree possible. The regulatory reforms since the Global Financial Crisis, both at the international and domestic level, have substantially increased the instruments available to policymakers. Consequently, the number of potential interactions if tools are in effect at the same time has also gone up significantly. Policymakers need to take such interactions into account when setting the optimal levels of their respective policies.

In this paper, we have assessed some of the interactions of macroprudential tools, including sectoral capital requirements, the countercyclical capital buffer, as well as loan-to-value limits, in a sectoral DSGE model with interest rate stickiness. Staggered interest rates are an important friction that influence the transmission of capital instruments, which primarily work through interest rates. The model allows us to calculate the optimal (welfare maximising) calibration of these policies, and perform counterfactual exercises to assess their effects on the economy. While these instruments lead to the expected improvement in economic indicators, they would not have been able to completely prevent the Great Recession.

We have left a number of possible extensions to future research. First, additional instruments, such as loan-to-income limits, could be introduced. Second, some of the policies in our model could be implemented in different ways. For example, the LTV limit could be designed as an occasionally binding constraint, and the setting of the CCyB could be modelled in a more asymmetric way, i.e. a slow build-up phase follow by a sudden release once a downturn occurs. Third, different objective functions could be tried to determine the optimal setting of different policies.

7 References

Aikman, D., Bridges, J., Kashyap, A. and Siegert, C., 2019. Would macroprudential regulation have prevented the last crisis? Journal of Economic Perspectives, 33(1), pp.107-30.

Aikman, D., Giese, J., Kapadia, S. and McLeay, M., 2019. Targeting financial stability: macroprudential or monetary policy?

Andries N. and Billon S.2014.'Retail bank interest rate pass-through in the Euro area: An empirical survey'.Economic Systems 40 (2016) 170–194.

BCBS (2019). Sixteenth progress report on adoption of the Basel regulatory framework.

Benes, J., and M. Kumhof. 2011. 'Risky Bank Lending and Optimal Capital Adequacy Regulation.' IMF Working Paper No. 11/130.

Bernanke, B. S., M. Gertler, and S. Gilchrist. 1999, 'The financial accelerator in a quantitative business cycle framework'. Handbook of Macroeconomics, Elsevier.

Berstein S., and R. Fuentes, 2002, "From Policy Rate to Bank Lending Rates: the Chilean Banking Industry," Paper presented at the Sixth Annual Conference of the Central Bank of Chile, December.

Bianchi, J.: 2011, 'Overborrowing and Systemic Externalities in the Business Cycle'. American Economic Review 101(7), 3400 -3426.

Bianchi, J. and Mendoza, E.G., 2010. Overborrowing, financial crises and'macro-prudential'taxes (No. w16091). National Bureau of Economic Research.

Berstein, S. and Fuentes, J., 2004. Is there Lending rate stickiness in the Chilean banking industry? Working paper, 2004.

Bluwstein K., Brzoza-Brzezina M., Gelain P.and Kolasa M.2018, 'Multi-period loans, occasionally binding constraints and monetary policy: a quantitative evaluation'.Bank of England Staff Working paper no.749.

Boissay , F. and Collard, F., 2016. Macroeconomics of bank capital and liquidity regulations. BIS working paper no.596

Bonciani, D. and Van Roye, B., 2016. Uncertainty shocks, banking frictions and economic activity. Journal of Economic Dynamics and Control, 73, pp.200-219.

Burgess, S., Fernandez-Corugedo, E., Groth, C., Harrison, R., Monti, F., Theodoridis, K. and Waldron, M., 2013. The Bank of England's forecasting platform: COMPASS, MAPS, EASE and the suite of models. documento de trabajo, (471).

Calvo, G. A.: 1983, 'Staggered prices in a utility-maximizing framework'. Journal of Monetary Economics 12(3), 383-398.

Campbell, J. Y. and J. F. Cocco: 2015, 'A Model of Mortgage Default'. The Journal of Finance 70(4), 1495-1554.

Christiano, L. J., R. Motto, and M. Rostagno: 2014, 'Risk Shocks'. American Economic Review 104(1), 27-65.

Clerc, L., A. Derviz, C. Mendicino, S. Moyen, K. Nikolov, L. Stracca, J. Suarez, and A. P. Vardoulakis: 2015, 'Capital Regulation in a Macroeconomic Model with Three Layers of Default'. International Journal of Central Banking 11(3), 9-63.

Collard, F., Dellas, H., Diba, B. and Loisel, O., 2017. Optimal monetary and prudential policies. American Economic Journal: Macroeconomics, 9(1), pp.40-87.

Darracq Pariès, M., Sørensen, C.K. and Rodriguez-Palenzuela, D., 2011. Macroeconomic propagation under different regulatory regimes: Evidence from an estimated DSGE model for the euro area. International Journal of Central Banking, 7(4), pp.49-113.

Driscoll, John C, and Ruth A Judson, 2013. Sticky deposit rates. Federal Reserve Board Working Paper.

Ferreira, L.N. and Nakane, M.I., 2015. Macroprudential Policy in a DSGE Model: anchoring the countercyclical capital buffer. FEA/USP.

Financial Policy Committee, 2016. The Financial Policy Committee's approach to setting the countercyclical capital buffer. London: Bank of England.

Forlati, C. and L. Lambertini: 2011, 'Risky Mortgages in a DSGE Model'. International Journal of Central Banking 7(1), 285-335.

Galati, G. and Moessner, R., 2018. What do we know about the effects of macroprudential policy?. Economica, 85(340), pp.735-770.

Gambacorta, L. and Karmakar, S., 2016. Leverage and risk weighted capital requirements.

Gelain, P. and Ilbas, P., 2017. Monetary and macroprudential policies in an estimated model with financial intermediation. Journal of Economic Dynamics and Control, 78, pp.164-189.

Gerali, A., S. Neri, L. Sessa, and F. M. Signoretti: 2010, 'Credit and Banking in a DSGE Model of the Euro Area'. Journal of Money, Credit and Banking 42, 107-141.

Goodhart, C. A. E., A. K. Kashyap, D. P. Tsomocos, and A. P. Vardoulakis: 2013, 'An Integrated Framework for Analyzing Multiple Financial Regulations'. Inter- national Journal of Central Banking 9(1), 109-144.

Greenwald D. The Mortgage Credit Channel of Macroeconomic Transmission. Working paper 2017.

Hannan, T. and Berger,N. (1991). The Rigidity of Prices: Evidence from the Banking Industry. The American Economic Review, 81(4), pp. 938-945.

Hodbod A., Huber S. and Vasilev K.2016 'Sectoral Risk Weights and Macroprudential Policy'. Working paper.

Iacoviello, M.: 2005, 'House Prices, Borrowing Constraints, and Monetary Policy in the Business Cycle'. American Economic Review 95(3), 739-764.

Ingholt, M.M., 2019. Multiple credit constraints and time-varying macroeconomic dynamics (No. 137). Danmarks Nationalbank Working Papers.

Jeanne, O. and A. Korinek: 2010, 'Excessive Volatility in Capital Flows: A Pigouvian Taxation Approach'. American Economic Review 100(2), 403-407.

Kahou, M.E. and Lehar, A., 2017. Macroprudential policy: A review. Journal of financial stability, 29, pp.92-105.

Karmakar, S., 2016. Macroprudential regulation and macroeconomic activity. Journal of financial stability, 25, pp.166-178.

Kiyotaki, N. and J. Moore: 1997, 'Credit Cycles'. Journal of Political Economy 105(2), 211-248.

Kobayashi, T. 2008. “Incomplete Interest Rate Pass-Through and Optimal Monetary Policy.” International Journal of Central Banking 4 (3): 77–118.

Lowe, P. and T. Rohling (1992), ‘Loan Rate Stickiness: Theory and Evidence’, Research Discussion Paper No. 9206, Reserve Bank of Australia.

Lozej, M., Onorante L and A. Rannenberg (2017), ‘Countercyclical Capital Regulation in a Small Open Economy DSGE Model ’, Research Technical Paper No.03/RT/2017, Central Bank of Ireland.

Martinez-Miera, D., and J. Suarez. 2012. ’A Macroeconomic Model of Endogenous Systemic Risk Taking.’ CEPR Discussion Paper No. 9134.

Meh, C., and K. Moran. 2010. ’The Role of Bank Capital in the Propagation of Shocks.’ Journal of Economic Dynamics and Control 34 (3), 555–76.

Mendicino, C., Nikolov, K., Suarez, J. and Supera, D., 2018. Optimal dynamic capital requirements. Journal of Money, Credit and Banking, 50(6), pp.1271-1297.

Mester, L., and Saunders, A. 1991. When does the prime rate change? Unpublished manuscript. Federal Reserve Bank of Philadelphia, Philadelphia.

Moazzami, B., 1999. ’Lending rate stickiness and monetary transmission mechanism: the case of Canada and the United States’. Applied Financial Economics 9, 533–538.

Nakajima J. & Teranishi Y., 2009. The Evolution of Loan Rate Stickiness Across the Euro Area. IMES Discussion Paper Series 09-E-10, Institute for Monetary and Economic Studies, Bank of Japan.

Neumark, D. and Sharpe,S. (1992). Market Structure and the Nature of Price Rigidity: Evidence from the Market for Consumer Deposits. Quarterly Journal of Economics, 107(2), pp. 657-680.

Nier, E. and Baumann, U., 2006. Market discipline, disclosure and moral hazard in banking. Journal of Financial Intermediation, 15(3), pp.332-361.

Nookhwun, N., and Tsomocos, D. (2017). "Mortgage Default, Financial Disintermediation and Macroprudential Policies", mimeo

Quint, D. and P. Rabanal: 2014, ’Monetary and Macroprudential Policy in an Estimated DSGE Model of the Euro Area’. International Journal of Central Banking 10(2), 169-236.

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

Repullo, R., and J. Suarez. 2013. 'The Procyclical Effects of Bank Capital Regulation.' Review of Financial Studies 26 (2), 452–90.

Smets, F. and Wouters, R., 2007. Shocks and frictions in US business cycles: A Bayesian DSGE approach. American economic review, 97(3), pp.586-606.

Sorenson C. and Werner T.2006.'Bank Interest rate pass-through in the Euro area: A cross country comparison'.ECB working paper no. 580/January 2006.

Van den Heuvel, S. 2008. 'The Welfare Cost of Bank Capital Requirements.' Journal of Monetary Economics 55 (2), 298–320.

A Historical Series and the Estimated Shocks

Figure 16: All estimated shocks over the sample period.

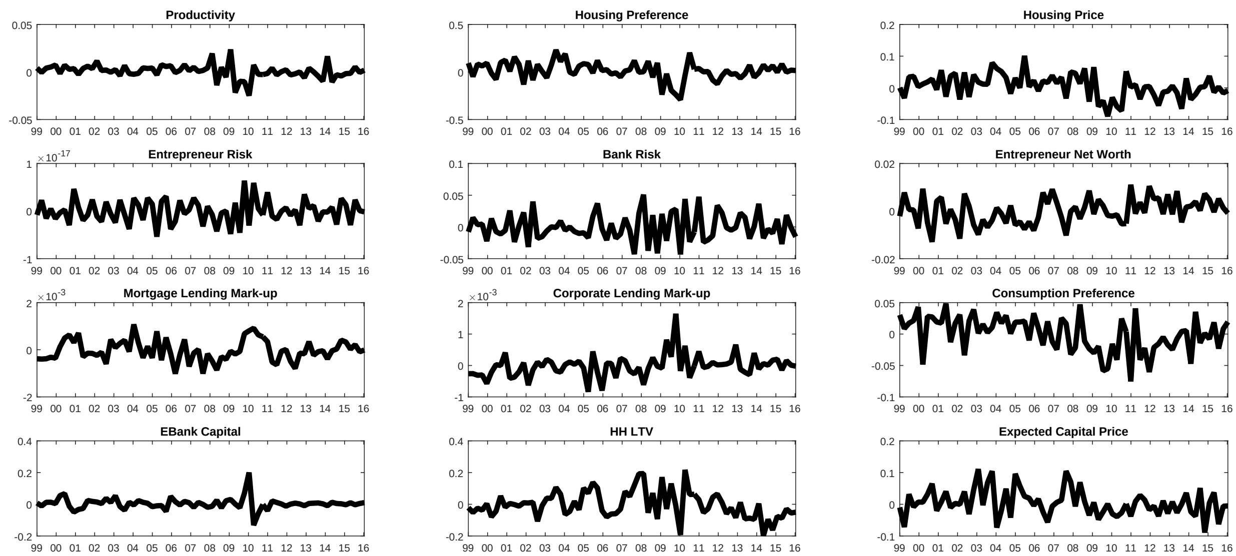
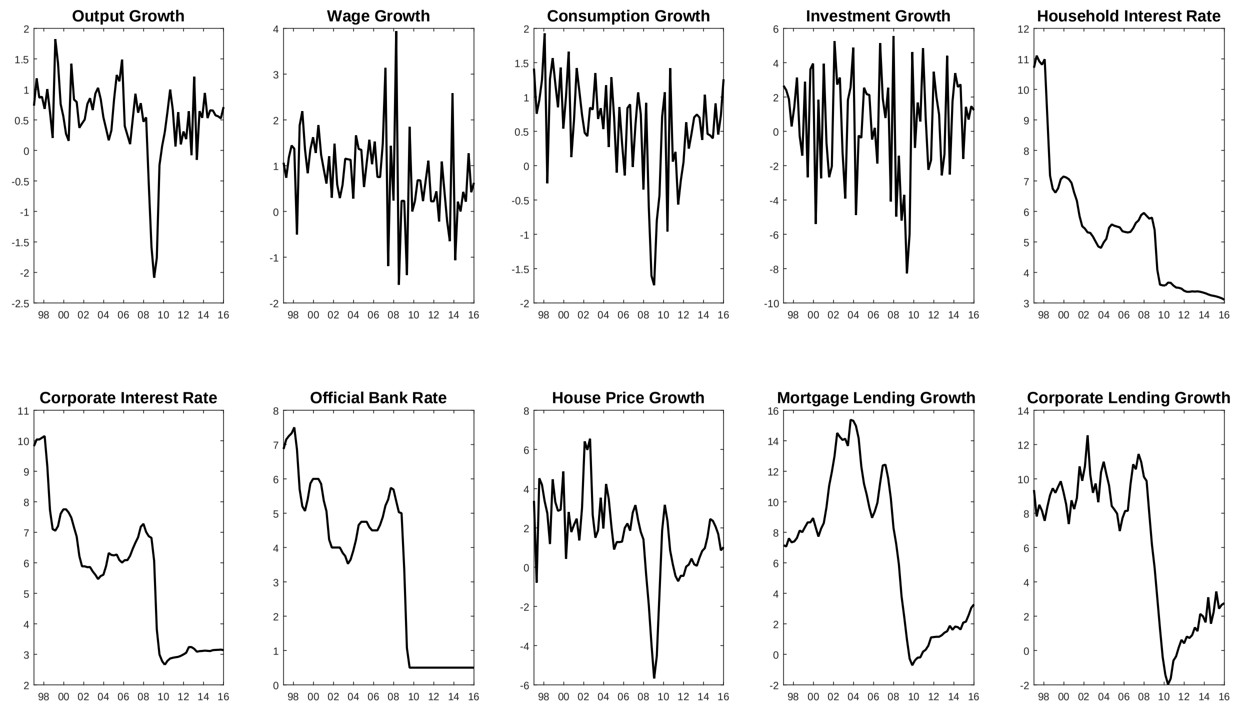


Figure 17: Observable variables used in the estimation.



B Cross country evidence on interest rate stickiness

We do a similar econometric exercise for France, Germany, Italy and Spain. We regress the monthly lending rate with 1 to 5 years of initial rate fixation on ECB policy rate and compare this with the regression of interest floating rate loans on ECB policy rate. We use the data from ECB Statistical Data warehouse.For the fixed rate loans, we use effective interest rate data for loans to corporations with an initial rate fixation period of over one to five years. For the floating rate loans, we use effective interest rate data for loans to corporations of (over EUR 1M) and an initial rate fixation period of up to one year.

We find similar results for the Eurozone countries. The response of the lending rate on impact (i.e. during the same month) is very small. In case of variable interest rate loans,the bulk of adjustment takes place in the following period, whereas the adjustment in fixed rate loans is reflected over a longer period.

Table 7: Regression of 1 to 5 year lending rate on ECB policy rate

Regressor	France	Germany	Italy	Spain
$ß_t$	0.054***	0.015***	0.014**	0.0027
Δ $ß_{t-1}$	0.257***	0.246***	0.258***	0.151**
Δ $ß_{t-2}$	0.316***	-0.009	0.124***	0.215**
Δ $ß_{t-3}$	0.294***	0.134***	0.17***	0.203**
Δ $ß_{t-4}$	-0.249*	-0.04	-0.119**	-0.049
Δ $ß_{t-5}$	0.366***	0.033	-0.09	-0.047**
constant	0.105***	0.035***	0.046**	0.014

Table 8: Regression of floating year lending rate on ECB policy rate

Regressor	France	Germany	Italy	Spain
$ß_t$	0.0729***	0.137***	0.034**	0.045**
Δ $ß_{t-1}$	0.766***	0.481***	0.597***	0.670**
Δ $ß_{t-2}$	- 0.009	0.389***	0.251***	0.203
Δ $ß_{t-3}$	0.577***	0.1915	0.284***	0.466**
Δ $ß_{t-4}$	-0.07	-0.157	0.049	-0.333*
Δ $ß_{t-5}$	0.09	0.017	0.0165	-0.0165
constant	0.139***	0.158***	0.08**	0.153**

For France, in response to a 1 percentage point change in policy rate, there is less than 0.05 percentage point change in the fixed term lending rate on impact. Around 0.25 percentage point change in interest rate is passed through during the following month and around 0.3 percentage point change is passed through during the third and fourth months after the policy rate change.

For the floating interest rate loans, the response on impact is also low. However, around 76 percent of the pass through takes place in the following month and there is a complete pass through by the end of four months.

For Germany, in response to a 1 percentage point change in policy rate, there is less than 0.015 percentage point change in the fixed term lending rate on impact. Around 0.25 percentage point change in interest rate is passed through during the following month and around 0.13 percentage point change is passed through during the fourth month after the policy rate change.

For the floating interest rate loans, the response on impact is also low. However, around 48 percent of the pass through takes place in the following month and there is a complete pass through by the end of four months.

For Italy, in response to a 1 percentage point change in policy rate, there is less than 0.015 percentage point change in the fixed term lending rate on impact. Around around 0.26 percentage point change in interest rate is passed through during the following month and around 0.12 and 0.17 percentage point change is passed through during the third month and fourth months after the policy rate change.

For the floating interest rate loans, the response on impact is also low. However, around 60 percent of the pass through takes place in the following month and there is a complete pass through by the end of four months.

For Spain, in response to a 1 percentage point change in policy rate, there is less than 0.01 percentage point change in the fixed term lending rate on impact. Only around 0.15 percentage point change in interest rate is passed through during the following month and around 0.2 change is passed through during the third month and fourth months after the policy rate change.

For the floating interest rate loans, the response on impact is also low. However, around 67 percent of the pass through takes place in the following month and there is a complete pass through by the end of four months.

To sum up, there is a clear pattern which emerges for all the four Eurozone economies. The response of fixed term lending rates on impact is very low. Around 25 per cent of the pass through takes place in the following period and around 20 to 30 per cent of the pass through takes place in the third and fourth months. Overall, the pass through of interest rate for fixed term loans is incomplete as observed in the UK data.

For the floating interest rate loans, the on impact is also low. However, around 50 to 70 percent of the pass through takes place in the following month and there is a complete pass through by the end of four months.

On the whole, we find that interest rate pass through is fastest in France as compared to Germany where it is the slowest among the four Eurozone economies.

C Posterior distributions of all estimated parameters

Figure 18: Posterior Parameter Distributions

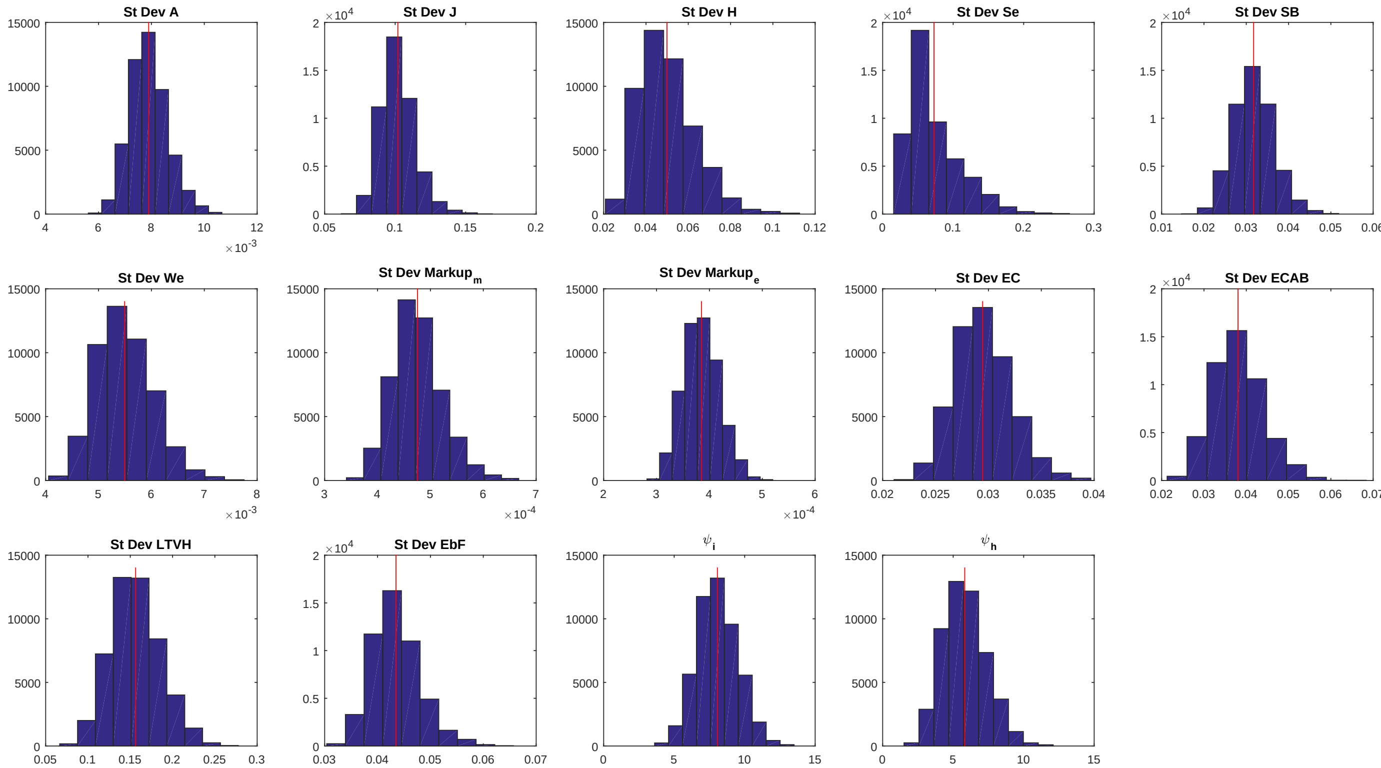
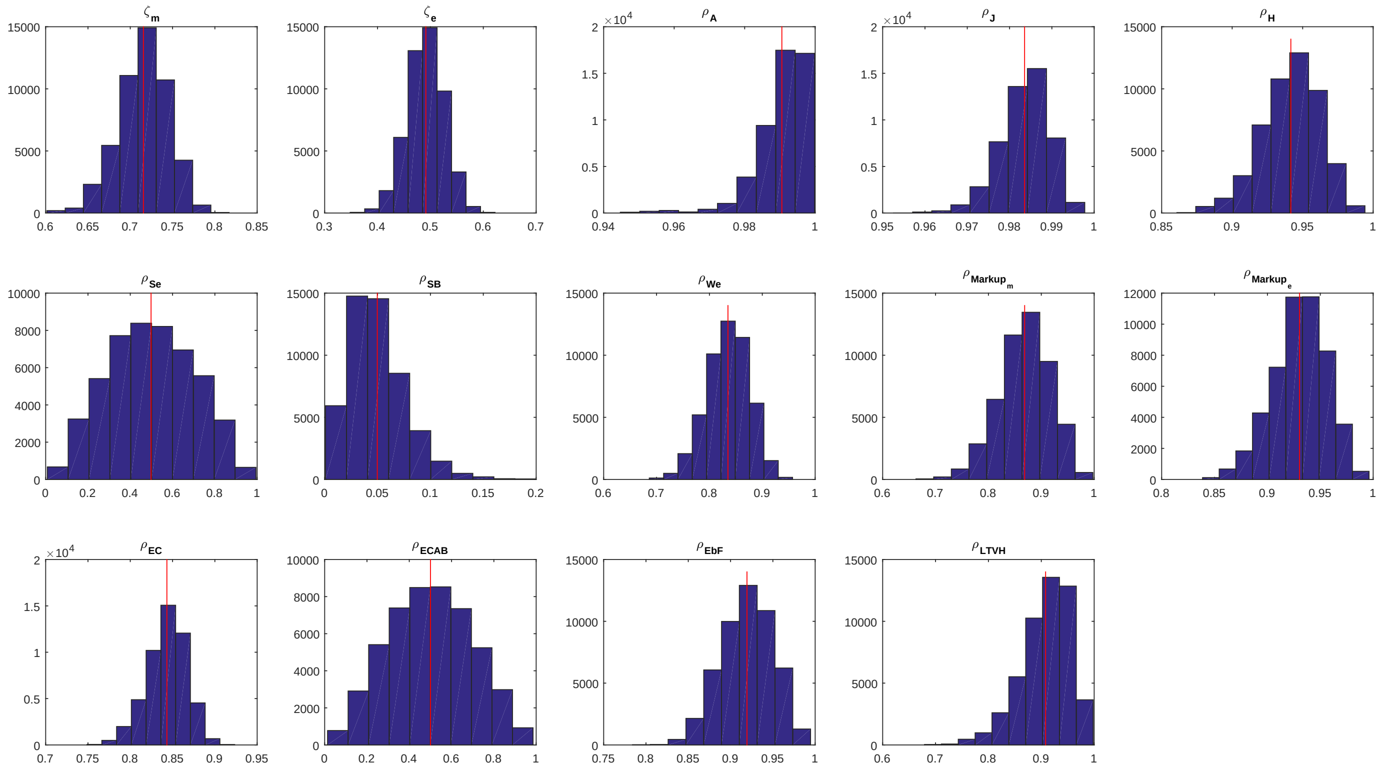


Figure 19: Posterior Parameter Distributions



D Model Overview and FOCs

This is a infinite time horizon model with patient and impatient households.The other key agents in the model are entrepreneurs, banks,deposit insurance agency, final/investment/housing goods producers.

Households

There are two types of households, patient and impatient, with patient households having a higher discount factor as in Iacoviello (2015).Both patient and impatient households have concave utility functions and derive utility from consuming goods, housing and leisure. The individual households are a part of a representative dynasty,which provides perfect risk sharing within the group. Thus, all individual households within the type are identical.Even if the individuals face idiosyncratic shocks, they are perfectly insured within their dynasty and hence consume and save/borrow identically.Both households supply labour in a competitive labour market.

Patient households

In equilibrium, patient households are savers who hold deposit with banks and buy houses with their own funds.

The objective function of the patient households (as is the case with impatient households) includes utility from consumption goods and housing and dis utility from labour.

$$\max_{c_t^s, L_t^s, D_t, H_t^s} E_t \sum_{t=0}^{\infty} \beta_s^t [log(c_t^s) + vlog(H_t^s) - \frac{(L_t^s)^{1+\eta}}{1+\eta}] \tag{D.1}$$

This is subject to the following budget constraint:

$$c_t^s + q_t^H H_t^s + D_t = w_t L_t^s + q_t^H H_{t-1}^s (1-\delta) + D_{t-1} R_t^D + \pi_t \tag{D.2}$$

The term π_t includes profits of final goods producing firms and investment/housing production firms (which are owned by patient households), dividends from entrepreneurs and lumpsum transfers from deposit insurance agency.

The FOCs for deposit and Housing stock is given by:

$$U'(c_t^s) = \beta_s E_t[U'(c_{t+1}^s) R_{Dt}] \tag{D.3}$$

$$U'(c_t^s) q^H = E_t[\beta_s U'(H_{t+1}^s) + \beta_s U'(c_{t+1}^s)(1-\delta) q_{t+1}^H]; \tag{D.4}$$

Impatient households

Impatient households borrow from banks using their houses as collateral as in Bernanke, Gertler & Gilchrist (1999) . These mortgage loans are made on a limited liability non-recourse basis, implying that individual households default whenever the value of the house is lower than the outstanding mortgage loans.The value of the house depends both on aggregate shocks (which affect house prices) as well as an idiosyncratic shock which determines whether an individual borrower defaults. In equilibrium, borrowers with an idiosyncratic shock below a certain threshold default.In the case of default, the bank takes possession of the houses in which case it is subject to state verification costs.

The borrowing is subject to LTV (Loan to value) limit set by the regulator. It is similar to a borrowing/collateral constraint as in Kiyotaki & Moore (1997).

The objective function of the impatient households is the same as that of the patient households except for the discounting factor:

$$\max_{c_t^m, B_t^m, L_t, H_t^m} E_t \sum_{t=0}^{\infty} \beta_m^t [log(c_t^m) + vlog(H_t^m) - \frac{(L_t^m)^{1+\eta}}{1+\eta}] \tag{D.5}$$

The budget constraint of impatient households reflects their borrowings under limited liability:

$$c_t^m + q_t^H H_t^m - B_t^m = w_t L_t^m + \int_{\bar{\omega_t^m}}^{\infty} \left(\omega_t^m q_t^H H_{t-1}^m (1-\delta) B_{t-1}^m R_{t-1} \right) \, dF\omega_t^m + P_t \tag{D.6}$$

The term under the integral reflects the limited liability of the borrowers as they default on their loans when the idiosyncratic shock ω_t^m is below the threshold level of $\bar{\omega^m}_t$.

The default decision by the borrowers is given by:

$$\omega_t^m q_t^H H_{t-1}^m (1-\delta) <= B_{t-1}^m R_{t-1}^m \tag{D.7}$$

The threshold level of $\bar{\omega^m}_t$ satisfies:

$$\bar{\omega^m}_t q_t^H H_{t-1}^m (1-\delta) = B_{t-1}^m R_{t-1}^m \tag{D.8}$$

The LTV limit (or the borrowing constraint) is given by:

$$[B_t^m - (1-rp)B_{t-1}^m]R_t <= \epsilon_t E_t[q_{t+1}^H[H_t^m - H_{t-1}^m(1-\delta)]] \tag{D.9}$$

where rp is the loan repayment rate and ϵ_t is the LTV limit.

The limit always binds in the steady state and it's neighborhood.

The FOCs for Mortgage loans and Housing stock is given by:

$$E_t U'(c_t^s) - \beta_m U'(c_{t+1}^s)(R_t^m(1-def_{t+1})) - \lambda_t R_t^m + \lambda_{t+1}(1-rp)(1-def_{t+1})R_{t+1}^m = 0 \tag{D.10}$$

$$E_t U'(c_t^s) q^H = \beta_m U'(H_{t+1}^s) + \beta_s U'(c_{t+1}^s)(1-Gm_{t+1})(1-\delta)q_{t+1}^H + \lambda_t(\epsilon_t q_{t+1}^H) - \lambda_{t+1}(\epsilon_{t+1} q_{t+2}^H)(1-\delta) \tag{D.11}$$

where def is the probability of default and the function Gm() represents the proportion of housing stock taken over by the bank for defaulted loans.λ_t is the lagrange multiplier on the LTV constraint.

Entrepreneurs

Entrepreneurs are risk neutral agents who own and maintain the stock of physical capital. They rent capital to the final goods producing firms. Entrepreneurs derive utility from transferring part of their wealth to the saving dynasty (paying dividends) and retaining the rest for the next period (retained earnings). Entrepreneurs invest in capital goods and finance their investment by means of their own funds (net worth) and borrowings from banks. Similar to mortgage loans, these are limited liability non-recourse loans and hence subject to default by individual entrepreneurs in the event of value of assets falling below the outstanding loans.The value of the capital depends both on aggregate shocks (which affect house prices) as well as an idiosyncratic shock which determines whether an individual entrepreneur defaults. In equilibrium, borrowers with an idiosyncratic shock below a certain threshold default. As in the case of households, assets are seized by banks and subject to costly state verification costs.

$$\max_{K_t, B_t^e} E_t(W_{t+1}^e) \tag{D.12}$$

$$W_{t+1}^e = max[\omega_{t+1}^e(r_{t+1}^k + (1-\delta)q_{t+1}^K K_t) - R_t^F b_t^e, 0] \tag{D.13}$$

The default decision of the entrepreneurs is given by:

$$\omega_t^e q_t^H K_{t-1}(1-\delta) <= K_{t-1} R_{t-1}^f \tag{D.14}$$

The threshold level of $\bar{\omega^m}_t$ satisfies:

$$\bar{\omega^e}_t q_t^K K_{t-1}^m (1-\delta) = B_{t-1}^e R_{t-1}^f \tag{D.15}$$

As borrowing is subject to LTV limit as follows:

$$[B_t^e - B_{t-1}^e(1-rp)]R_t^f = \epsilon_t E_t[q_{t+1}^F[K_t - K_{t-1}(1-\delta)]] \tag{D.16}$$

Dividend rule:

A fixed proportion of wealth χ^e is paid out as dividends. This simple dividend paying rule for the entrepreneurs is given by:

$$c_t^e = \chi^e W_t^e \tag{D.17}$$

As a result the retained earnings by the entrepreneurs is given by:

$$n_t^e = (1-\chi^e)W_t^e \tag{D.18}$$

The balance sheet identity of the entrepreneurs is :

$$n_t^e + B_t^e = q_t^K K_t \tag{D.19}$$

Bank

Banks are financial intermediaries who channel savings from the savers to the borrowers.On the asset side of the banks, there are loans to households (mortgage lending) and entrepreneurs (business lending) respectively. As described earlier, these loans may default depending on aggregate state shocks and idiosyncratic borrower shocks in which case the banks seize the assets subject to state verification costs (these can also be viewed as bankruptcy costs).

On the liability side, there are deposits held by the patient households and equity capital held by the bankers. Deposits are insured by the Deposit Insurance agency. There is a capital adequacy requirement set by the regulator which along with a penalty cost function, which determines the amount of equity capital held by the bankers.

The key feature of the model is that banks may also default depending upon the performance of their loan portfolios (aggregate shocks) and idiosyncratic shocks (on similar lines as the borrowers). The banks face an idiosyncratic shock to their returns on loans.Thus, in equilibrium, a fraction of banks below a certain threshold of the idiosyncratic shock level default. In case of default, the bank loan assets are also subject to possession by the deposit insurance agency and costly state verification.

The banks' balance sheet identity is as follows:

$$n_t^b + D_t = B_t^m + B_t^e \tag{D.20}$$

The maximization problem of the bank is given by:

$$\max_{R_t^{mi}, R_t^{fi}} E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t [\{(1-G_{t+1}^H)(\widetilde{R_t^{mi}})(B_t^{mi}) + (1-G_{t+1}^F)\widetilde{R_t^{fi}} B_t^{ei}\} - (1-bankdef.prob)R_t^D D_t + Penaltycost] \tag{D.21}$$

$$\widetilde{R_t^{mi}} = (1-def.prob^m)R_t^{mi} + G_{t+1}^m(1-\mu^m)(R_t^{mi}/\bar{\omega}_{t+1}^m) \tag{D.22}$$

$$\widetilde{R_t^{fi}} = (1 - def.prob^e)R_t^{fi} + G_{t+1}^e(1-\mu^e)(R_t^{fi}/\bar{\omega}_{t+1}^e) \tag{D.23}$$

The demand for Loans is given by:

$$B_t^{mi} = (\frac{R_t^{mi}}{R_t^m})^{-\tau} B_t^m \tag{D.24}$$

$$B_t^{ei} = (\frac{R_t^{fi}}{R_t^f})^{-\tau} B_t^e \tag{D.25}$$

Rmi/Rfi is the rate if interest charged by individual bank,τ is the elasticity of substitution between banks and determines their market power. μ is the proportion of state verification/bankruptcy costs.

Penalty cost function

Penalty costs are modeled as a non pecuniary gain in utility if the capital adequacy ratio is higher than the minimum capital requirement and a non pecuniary cost if the capital adequacy ratio is lower than the minimum capital requirement.

$$Penaltycost_t = \nu^b \frac{[\frac{\phi_t^b}{\bar{\varphi}_t}]^{1-\sigma} - 1}{1-\sigma} \tag{D.26}$$

The above functional form,based on Nookhwun & Tsomocos (2018) builds in a non-linearity in the penalty costs.The marginal gains of having excess capital are decreasing whereas the marginal costs of having a shortfall in capital are increasing, whenever σ is greater than 1. This creates an incentive for banks to maintain capital at a higher level as compared to the minimum regulatory requirement. In reality, we find that banks do maintain capital buffer over what is the minimum required.The parameter ν^b determines the weight attached to this penalty costs.

Interest rate stickiness

Although, interest rate stickiness can be attributed to various reasons such as switching costs,menu costs, market structure, regulation etc.,we find the one of the main sources of interest rate sluggishness is the existence of fixed interest loans.

We introduce interest rate stickiness in a broader sense by modeling it as in Calvo (1983). This approach also has the benefit that it includes all possible sources of interest rate sluggishness in a reduced form (including the effect of long term fixed interest loans).It is assumed that only a ξ proportion of banks are able to change their interest rates in a given period, whereas the remaining 1-ξ proportion of banks are not able to change their interest rate. This staggered interest rate setting implies that the composite interest rate in the economy is an average of the current interest rate charged by the fraction of banks who can change the interest rate and the previous period interest rate. To micro-found the staggered interest rate setting, we assume that there is imperfect competition in the banking sector. Banks offer differentiated loan products as in Gerali et al (2010) and are able to set their interest rate in the monopolistically competitive loan market.The borrowers takes a composite loan product comprising of all the aforesaid differentiated banking services.The composite interest rate paid by the borrowers is thus staggered on account of the Calco friction.In short,we extend the New Keynesian approach to goods market to the loan markets so as to generate interest rate stickiness.

The FOCs for the interest rates are as follows.The FOC is similar to the FOC for price in a standard New Keynesian model with goods price stickiness:

$$R_t^{mi} = \frac{\tau}{\tau - 1} \frac{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t MC_t}{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t rm_t} \tag{D.27}$$

$$R_t^{fi} = \frac{\tau}{\tau - 1} \frac{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t MC_t}{E_t \sum_{t=0}^{\infty} \xi^t \beta_s^t rf_t} \tag{D.28}$$

$$MC_t = \lambda_{st+1}[(1 - bankdef.prob)((1 - \phi_t))R_{Dt} + \frac{\nu^b(\phi_t/\varphi_t)^{(1-\sigma)}}{(B_t^{mi} + B_t^{ei})}](R_t^m)^\tau B_t^m \tag{D.29}$$

As in the New Keynesian model with price stickiness, the interest rate charged by banks is a function of present discounted value (with the stickiness parameter) of present and future marginal cost times the mark up. The marginal cost includes the interest rate paid on deposits (in a competitive deposit market) and the penalty cost associated with the deviation from the regulatory capital requirement. The only difference from the standard New Keynesian version is the presence of borrower and bank defaults in the interest FOC for interest rate equation

Deposit Insurance Agency

The deposit insurance agency insures the deposits. The assets of the defaulting banks are taken over by the agency and is subject to bankruptcy costs.The difference between the amount of deposits and the value of assets realized assets is recovered by the charging a lumpsum tax on households.

Final goods producing Firms

There is a unit mass of perfectly competitive firms which combine capital and labour to produce the consumption good which is the numeraire.The firms rent capital from entrepreneurs. The firms are owned by patient households. They produce the final goods using a standard Cobb Douglas technology.

$$Y_t = A_t K_{t-1}^{\alpha} L_t^{1-\alpha} \tag{D.30}$$

Capital goods and Housing production

These are competitive firms which buy finished goods and produce capital goods /housing subject to quadratic adjustment costs.These firms produce new units of capital and housing using consumption goods which are then sold to entrepreneurs and households,respectively, at prices qK and qH. They represent the supply side of the capital goods/housing and pin down the equilibrium asset prices.These firms are also owned by the patient households.

They maximize their profits as follows:

$$\max_{I_t} E_t \sum_{i=0}^{\infty} \beta_s^t \{\frac{c_t^s}{c_{t+1}^s}\}[q_{t+i}^K I_{t+i} - \{1 + g[\frac{I_{t+i}}{I_{t+i-1}}]\}] \tag{D.31}$$

$$\max_{I_t^H} E_t \sum_{i=0}^{\infty} \beta_s^t \{\frac{c_t^s}{c_{t+1}^s}\}[q_{t+i}^H I_{t+i} - \{1 + g[\frac{I_{t+i}^H}{I_{t+i-1}^H}]\}] \tag{D.32}$$

Macro Prudential Policy

The Macro Prudential policy pursued by the regulator includes a minimum capital requirement (also known as capital adequacy ratio) for the banks and a maximum loan to value ratio (LTV) for the borrowers. The regulator also sets a countercyclical capital rule which responds to the credit growth in the economy.

$$CR_t = C\bar{R} + \psi^{cr} log(B_t/\bar{B}) \tag{D.33}$$

The first part of the rule is the static minimum capital requirement which the banks are supposed to hold at any point of time. The second part is the counter cyclical component,which tracks the credit growth in the economy.

On similar lines,following is the rule for the LTV limit:

$$LTV_t = L\bar{T}V - \psi^{LTV} log(B_t/\bar{B}) \tag{D.34}$$