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Multi-period loans, occasionally binding constraints and monetary policy: a quantitative evaluation

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Abstract

We study the implications of multi-period mortgage loans for monetary policy, considering several realistic modifications — fixed interest rate contracts, lower bound constraint on newly granted loans, and possibility for the collateral constraint to become slack — to an otherwise standard DSGE model with housing and financial intermediaries. We estimate the model in its nonlinear form and argue that all these features are important to understand the evolution of mortgage debt during the recent US housing market boom and bust. We show how the nonlinearities associated with the two constraints make the transmission of monetary policy dependent on the housing cycle, with weaker effects observed when house prices are high or start falling sharply. We also find that higher average loan duration makes monetary policy less effective, and may lead to asymmetric responses to positive and negative monetary shocks.

Key words: Mortgages, fixed-rate contracts, monetary policy.

JEL classification: E44, E51, E52.

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1 Introduction

As highlighted by the recent financial crisis, mortgage markets can play an important role in driving business cycles. Moreover, they strongly interfere with macroeconomic policies, and monetary policy in particular. These observations led to an unprecedented boom in creation (and publication) of macroeconomic models featuring financial intermediation, housing markets and mortgage loans, the early examples of which were Iacoviello (2005), Iacoviello and Neri (2010) or Gerali et al. (2010).

In spite of their apparent importance, structural modeling of mortgage and housing markets usually assumes – needless to say, counterfactually – that mortgage loans are granted for a single period, which in most models corresponds to one quarter. This makes it impossible to incorporate fixed-rate contracts, despite their prevalence in some countries, and most notably in the US. Second, most models that follow the seminal contribution of Iacoviello (2005) and build financial imperfections on the concept of collateral constraints ignore another important fact – that such constraints usually bind only occasionally. However, while a potential creditor can be prevented from taking a loan, she cannot be forced to take one. Last, but not least, another nonlinearity associated with mortgages seems important – a lower bound on new loans. Again, there is an asymmetry at play: a borrower can be prevented from taking a new loan, but cannot be forced to accelerate the repayment of old loans when the collateral value declines (which, for a given LTV ratio imposed on total debt, would require new loans to become negative).

This brings three features of mortgage markets to our attention: multiperiodicity of loan contracts, the occasionally binding nature of collateral constraints and the existence of a lower bound for new loans. It should be highlighted that these are not only potentially important stand-alone features of the mortgage market, but they also can enter into powerful interactions. For instance, both the already mentioned fixed-rate contracts and the lower bound on new loans make sense only in a multi-period contracting setting. While all three features have been dealt with in the literature before, we are not aware of any study that would offer a thorough, quantitative assessment of the role they played in shaping macroeconomic dynamics, or that would explain how they work and interact with each other, especially in the context of monetary policy. We believe that these are highly relevant topics and try to fill the existing gap in the literature.

Our paper is related to the body of literature coping with multi-period mortgages (or, more generally, long-term housing finance). Many of these contributions deal with different interesting issues, but abstract from policy considerations. For example, Campbell and Cocco (2003) study how households should optimally choose between fixed-rate and adjustable-rate mortgages given the important welfare implications that such a choice implies. Hurst and Stafford (2004) and Li and Yao (2007) both focus on consumption smoothing, the former showing how homeowners use housing equity to smooth their consumption over time, and the latter demonstrating how changes in house prices affect consumption and welfare of young, middle-aged and old homeowners in a life-cycle model. Chambers et al. (2009a) and Chambers et al. (2009b) look at equilibrium home ownership rates. Garriga and Schlagenhauf (2009), Chatterjee and Eyigungor (2011), and Corbae and Quintin (2011) analyze equilibrium foreclosures. Kydland et al. (2012) develop a multi-period loans model in which loans taken out in a given period are only used to finance new homes constructed in the same period, and study the business cycle implications of a longer time to build in housing construction. Iacoviello (2015) does not explicitly model long term financing, but introduces a quadratic loan portfolio adjustment cost, which penalizes entrepreneurs for changing their loan balances too quickly between one period and the next, to capture the idea that the volume of lending changes slowly over time. On the firms side, it is also worth mentioning Gomes et al. (2016), who develop a tractable general equilibrium model that captures the interplay between nominal long-term corporate debt, inflation, and real aggregates.

As regards papers focusing on macroeconomic policy, the contributions are all very recent. Benes and Lees (2010) investigate the implications of the existence of multi-period fixed-rate loans for the behavior of a small open economy exposed to finance shocks and housing boom-bust cycles. Rubio (2011) studies how the proportion of fixed and variable rate mortgages affects business cycles and welfare in a DSGE model with housing. Calza et al. (2013) develop a DSGE model with two-period mortgage contracts, assuming that the existence of loans of different maturities reflects the distinction between variable rate and fixed rate contracts. Garriga et al. (2013) use the multi-period mortgage setup developed in Kydland et al. (2012) to analyze how monetary policy functions in such a context. Gelain et al. (2014b) use a version of the Kydland et al. (2012) framework to investigate whether a standard asset pricing model can account for the boom-bust patterns in U.S. data over the period 1995-2012. Gelain et al. (2014a) use the same framework, but in a general equilibrium context, to revisit the leaning-against-the-wind argument. Robinson and Yao (2016) examine the implications of loan-to-value policies for the business and credit cycles using an estimated DSGE model with housing and long-term mortgage debt. Alpanda and Zubairy (2017) compare the effectiveness of monetary policy, housing-related fiscal policy and macroprudential regulations in reducing household indebtedness in an estimated DSGE model featuring long-term fixed-rate borrowing. Finally, Andres et al. (2017) exploit the long-term debt framework to assess the effects of reforms in product and labor markets.

Last but not least, some motivation to study the effects of multiperiodicity of loans is also lent by empirical studies. Giuliodori (2005), Assenmacher-Wesche and Gerlach (2008), and Calza et al. (2013) all stress that having fixed or variable mortgage rates makes a large difference for the effects of monetary policy on house prices and real variables, e.g. residential investment, consumption and GDP. Moreover, these studies find that the monetary policy transmission is more effective in those countries where variable-rate mortgages are prevalent.

Our paper offers three contributions to the literature. First, we provide a Bayesian estimation of a DSGE model with housing and financial frictions, where mortgage contracts are multi-period, the collateral constraint faced by borrowers can be occasionally binding, and new loans are subject to a lower bound. This is the first estimation in the related literature that features at the same time those two (important, as we document) nonlinearities. To our knowledge, in the context of constrained households, only models with occasionally binding collateral constraints have been estimated so far in a few papers, see Guerrieri and Iacoviello (2017) and Bluwstein (2017). Second, the estimated model allows us to show period by period when and how the two nonlinearities, in interaction with multi-period loans, shaped the US financial and housing cycle in the past 25 years. Third, we demonstrate the implications of our multi-period loan setting with nonlinearities for the transmission of monetary policy.

More specifically, we construct a DSGE model with housing and financial intermediaries. In contrast to much of the literature, we allow loans to be multi-period and carry a constant interest rate over the contract duration. We also introduce two types of nonlinearities that have been recently highlighted in a different context by Guerrieri and Iacoviello (2014) and Justiniano et al. (2015). The first nonlinearity is related to the fact that households' collateral constraint might be only occasionally binding, which means that an increase in the value of collateralizable assets does not always translate one-to-one into an increase in mortgage debt. The second nonlinearity results from imposing a lower bound constraint on new loans, which can be interpreted as ensuring that borrowers cannot be forced to accelerate repayment of their (long-term) debt. To understand better the financial structure in our model, it is instructive to abstract away for a moment from the fact that we assume mortgages to be of a fixed-rate type. Then, a mortgage contract in our model can be thought of as a home equity loan as in Iacoviello (2005), but with the lower bound on new borrowing making it effectively a long-term loan. Whenever binding, this constraint prevents the borrower from being forced to prepay and thus undo some of the loans taken in the past. As a result, in some states of the world, past borrowing will matter for the current level of debt. This breaks the equivalence between one and multi-period debt, even when the mortgage cost is adjusted every period as under variable rate contracts.[1]

[1]Absent the lower bound on new borrowing, one and (adjustable rate) multi-period loans in our setup, as well as in the standard models with collateral constraints like Iacoviello (2005), are equivalent as they imply the same constraint on total debt, and the sequence of expected real interest rates for

We estimate the model in its nonlinear form using US data and the method developed by Guerrieri and Iacoviello (2017). We show that all of our extensions are important to understand the evolution of loans during the recent US housing market boom and bust. A standard DSGE model with housing, single period loans and a permanently binding collateral constraint generates a highly counterfactual series of mortgage loans. In contrast, we show that our framework is able to match the evolution of mortgage debt much better. In particular, and unlike in the standard model, our multi-period setting reproduces the fact that loans peaked almost two years after house prices did, and that their subsequent fall was moderate. Our estimation also allows us to precisely identify the periods when the two nonlinearities considered in our framework mattered. For instance, according to our estimation, the collateral constraint became slack in the second half of the housing market boom (i.e. between 2002 and 2007), while the lower bound constraint on new borrowing was most important during the credit crunch (between 2008 and 2013). Our interpretation of the latter is that during that episode banks wanted to restrict lending by more than they were able to. We treat these results not only as telling an interesting and plausible story about the US housing market developments, but also as a proof of significance of our extensions to the basic framework.

We next use our model to evaluate the impact of multiperiodicity and the two nonlinearities on the transmission of monetary policy. We show how the impact of unexpected changes in the monetary policy stance depends on the momentum of the housing cycle as the latter affects the degree to which the financial accelerator mechanism amplifies the initial impulse. The occasionally binding nature of the constraints can also generate significant asymmetry in responses to positive and negative shocks. The degree of this asymmetry and time-variation crucially depends on the average mortgage loan

a multi-period variable-rate loan equals the series of expected real interest rates for rolled-over single period loans. This makes our financing arrangements resemble home equity loans or refinancing, which is different from Kydland et al. (2012), who essentially consider first mortgages so that the distinction between one and multi-period loans is always relevant, even in the absence of constraints on earlier repayment.

maturity, making this characteristic of the mortgage market an important determinant of the strength and lags in the monetary policy transmission mechanism. Finally, we confirm the finding from the empirical literature that monetary policy is less effective under fixed than under variable rate loans.

The rest of the paper is structured as follows. Sections 2 and 3 present the model and its estimation. Section 4 demonstrates the importance of our extensions using the recent housing boom and bust in the US as an example. Section 5 discusses the implications of our model for monetary policy transmission. Section 6 concludes.

2 Model

We start from a standard medium-sized New Keynesian setup, extended to incorporate housing and credit frictions as in Iacoviello (2005), and modified to allow for multi-period loans. A key feature of our extension, particularly relevant in a multi-period contract environment, is that the collateral constraint is not assumed to hold with equality every period. Instead, borrowers' total debt burden can occasionally exceed or fall below the value of collateralizable assets.

Following the common practice in the DSGE literature, we include several frictions that make the impulse responses to monetary shocks implied by our model consistent with the VAR literature. These are: sticky prices, sticky wages and investment adjustment costs. We also include a redistributive fiscal sector, which helps us account for the heterogeneity between borrowers and lenders observed in the microdata.

Our model economy is populated by two types of households, capital producers, goods producers, and the government authorities. Below we sketch the optimization problems facing each class of agents, focusing particularly on those that make up the key ingredients of our extension. The full list of equations making up the equilibrium in our model can be found in the Appendix.

2.1 Households

To introduce credit, we distinguish between two types of households that differ in their subjective discount rates. Those relatively patient are indexed by P and make natural lenders, while the impatient group, denoted by I, are natural borrowers. The share of impatient households in population is ω. Within each group, a representative agent ι maximizes

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta_i^t \left[\varepsilon_{u,t} \ln c_{i,t}(\iota) + A\varepsilon_{h,t} \ln h_{i,t}(\iota) - \frac{n_{i,t}(\iota)^{1+\sigma_n}}{1+\sigma_n} \right] \right\} \tag{1}$$

for $i = \{I, P\}$, $\beta_I < \beta_P$ and $A > 0$. In the formula above, c_t is consumption, h_t denotes the housing stock, n_t is labor supply, while $\varepsilon_{u,t}$ and $\varepsilon_{h,t}$ stand for consumption and housing preference shocks.

Patient households' maximization is subject to a standard budget constraint

$$\begin{aligned} P_t c_{P,t} + P_{h,t}(h_{P,t} - (1-\delta_h)h_{P,t-1}) + P_{k,t}(k_t - (1-\delta_k)k_{t-1}) + D_t = \\ = W_{P,t}(\iota)n_{P,t}(\iota) + R_{k,t}k_{t-1} + R_{t-1}D_{t-1} + \Pi_t + T_{P,t} + \Xi_{P,t}(\iota) \end{aligned} \tag{2}$$

where $\delta_h \in (0,1)$, k_t denotes physical capital, $R_{k,t}$ is its rental rate, Π_t stands for the financial result of firms and the banking sector, $T_{i,t}$ is lump-sum net transfers, $P_{h,t}$ and $P_{k,t}$ denote housing and physical capital prices, $W_{i,t}$ is nominal wage, D_t stands for one-period deposits paying a risk-free rate R_t that is set by the central bank, and $\Xi_{i,t}$ is the payout from state-contingent securities traded between households of the same type and providing perfect insurance against household-specific labor income risk arising from wage stickiness.[2]

Impatient households do not accumulate physical capital nor hold any equity. They have access to multi-period mortgage loans, which are modeled as in Woodford (2001), i.e. as perpetuities with principal payments equal to a constant fraction $\frac{1}{m} \in (0,1]$ of

[2]The presence of these securities allows us to save on notation and drop indexing other households' allocations with ι.

outstanding debt so that m can be interpreted as average loan maturity, including possible prepayment that we do not consider among the set of choices made by households. As a result, outstanding mortgage debt S_t follows the law of motion

$$S_t = L_t + (1 - \frac{1}{m})S_{t-1} \tag{3}$$

where L_t denotes newly originated mortgages.

In line with the prevalence of fixed-rate mortgages observed in the US in recent decades, we model them as contracts for which the interest payments are fixed at origination and apply for the whole loan duration. Hence, impatient households' budget constraint can be written as (see e.g. Greenwald, 2017)

$$P_t c_{I,t} + P_{h,t}(h_{I,t} - (1 - \delta_h)h_{I,t-1}) + \Phi_{t-1} + \frac{1}{m}S_{t-1} = W_{I,t}(\iota)n_{I,t}(\iota) + L_t + T_{I,t} + \Xi_{I,t}(\iota) \tag{4}$$

where Φ_t is the total promised payment on existing fixed-rate loans that evolves according to

$$\Phi_t = (R_{h,t} - 1)L_t + (1 - \frac{1}{m})\Phi_{t-1} \tag{5}$$

where $R_{h,t}$ is the interest rate associated with loans originated at time t. This rate will be determined in equilibrium by the optimal behavior of banks.

Additionally, impatient households' optimization is subject to two additional constraints. The first one is a standard collateral constraint, which is given by the following inequality

$$R_t S_t \leq \vartheta(1 - \delta_h)\mathbb{E}_t\left\{P_{h,t+1}h_{I,t}\right\} \tag{6}$$

where $\vartheta > 0$ can be interpreted as a loan to value (LTV) ratio.

On top of this, we also introduce a lower bound constraint on the amount of new loans granted each period. Obviously, a loan cannot be negative, and this is the assumption implicitly introduced to the literature by Justiniano et al. (2015). Given what can be observed from the data on new loan originations (described in detail in Section

3), we make this constraint even stronger by setting a (possibly strictly positive) lower bound on the amount of newly created loans

$$L_t \geq \bar{l} P_t \tag{7}$$

where $\bar{l} \geq 0$. This constraint can be rationalized by noting that in reality the housing market is heterogeneous and some households do have access to mortgages regardless of the economic situation.[3] If $\bar{l} = 0$, the lower bound constraint can be interpreted as a non-negativity constraint on new credit, which effectively means that banks cannot force borrowers to accelerate repayment of loans granted in the past.

The collateral constraint (6) is assumed to apply only if the lower bound constraint on new loans is slack. In other words, whenever equation (6) implies $L_t < \bar{l} P_t$, new loans are equal to their lower bound $L_t = \bar{l} P_t$. This means that, similarly to Justiniano et al. (2015), our modeling setup allows for an increase in the observed LTV ratio above the level implied by bank policies during the episodes of plummeting house prices or sharp tightening of lending standards. It also provides an additional mechanism, on top of the possible slackness of the collateral constraint, that makes the effectiveness of policy interventions contingent on their scale and on the state of the economy.

Each household supplies differentiated labor in a monopolistically competitive fashion, with aggregation given by

$$n_{i,t} = \left[\int_0^1 n_{i,t}(\iota)^{\frac{1}{\mu_w}} d\iota \right]^{\mu_w} \tag{8}$$

for $i = \{I, P\}$ and $\mu_w > 1$. Nominal wages are assumed to be sticky as in the Calvo scheme. More specifically, each period only a randomly selected fraction $1 - \theta_w$ of households can reoptimize while the remaining wages are automatically indexed to the steady state inflation.

[3] Naturally, the way we introduce a lower bound on new loans can be considered ad-hoc. However, developing a fully-fledged heterogeneous household framework to derive this constraint from microfoundations goes much beyond the scope of this paper.

2.2 Firms

There are several types of firms in our model. Perfectly competitive final goods producers aggregate intermediate goods indexed by ν according to

$$y_t = \left[\int_0^1 y_t(\nu)^{\frac{1}{\mu}} d\nu \right]^{\mu} \tag{9}$$

where $\mu > 1$.

Intermediate goods producing firms operate in a monopolistically competitive environment and use the following production function

$$y_t(\nu) = \varepsilon_{z,t} k_{t-1}(\nu)^{\alpha} n_t(\nu)^{1-\alpha} \tag{10}$$

where $\varepsilon_{z,t}$ is exogenous productivity and homogeneous labor input is defined as

$$n_t(\nu) = [\omega n_{I,t}(\nu)]^{\gamma} [(1-\omega) n_{P,t}(\nu)]^{1-\gamma} \tag{11}$$

Intermediate firms are subject to nominal rigidities so that each period only a random fraction $1-\theta$ of them can reset their prices while the remaining ones adjust their prices to the steady state inflation. Since these firms are owned by patient households, they use their marginal utility to discount the future profits.

Finally, capital production is undertaken by perfectly competitive firms owned by patient households. They purchase the undepreciated capital from the previous period and produce new stocks according to the following formula

$$k_t = (1-\delta_k) k_{t-1} + \left(1 - \Gamma\left(\frac{i_{k,t}}{i_{k,t-1}}\right)\right) i_{k,t} \tag{12}$$

where $i_{k,t}$ are final goods used for capital investment while the adjustment costs function is parameterized such that $\Gamma(1) = \Gamma'(1) = 0$ and $\Gamma''(1) = \kappa \geq 0$.

2.3 Banks

Perfectly competitive banks collect deposits and use them to extend mortgage loans to impatient agents. Banks are owned by patient households, who receive profits or cover losses generated in the sector. Their problem is to maximize

$$\mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta_P^t \frac{\varepsilon_{u,t}}{c_{P,t} P_t} (\Phi_{t-1} + \frac{1}{m} S_{t-1} - L_t + D_t - R_{t-1} D_{t-1}) \right\} \tag{13}$$

subject to the balance sheet constraint

$$D_t = S_t \tag{14}$$

as well as the law of motion for debt (3) and promised interest payments (5). The solution to banks' optimization problem provides an equilibrium condition for the loan rate $R_{h,t}$.

2.4 Government

The fiscal authority follows a passive policy, purchasing a constant fraction g_y of final goods and financing their expenditures with lump sum taxes levied on households so that the government budget is balanced every period

$$P_t g_t = g_y P_t y_t = \omega T_{I,t} + (1-\omega) T_{P,t} \tag{15}$$

where P_t is the price of final goods. The tax policy is such that the share of impatient households in the total tax burden is fixed at τ.

The monetary authority sets the policy rate according to the standard Taylor-like rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\gamma_R} \left[\left(\frac{\pi_t}{\pi} \right)^{\gamma_\pi} \left(\frac{y_t}{y} \right)^{\gamma_y} \right]^{1-\gamma_R} \varepsilon_{R,t} \tag{16}$$

where variables without time subscripts denote their steady state values and $\varepsilon_{R,t}$ is a monetary policy shock.

2.5 Market clearing

The model is closed with a standard set of market clearing conditions. We assume that housing stock is fixed at the aggregate level at value h so that we have

$$h = \omega h_{I,t} + (1-\omega) h_{P,t} \tag{17}$$

The aggregate resource constraint is

$$y_t = \omega c_{I,t} + (1-\omega) c_{P,t} + i_{k,t} + i_{h,t} + g_t \tag{18}$$

where

$$i_{h,t} = \delta_h h \tag{19}$$

is housing investment compensating for housing depreciation.

3 Calibration and estimation

The model is partly calibrated and partly estimated. In what follows, we describe in detail the calibration and then move to the estimation part. Our country of reference is the US. The model and data frequency is quarterly.

The assumed parameter values for the calibration are reported in Table 1. Following the standard practice, a subset of parameters are taken from the literature or calibrated to match the long-run averages observed in the data. Households' utility is parameterized such that it implies a moderate Frisch elasticity of labor supply. The discount factor of patient households is set to obtain an annualized average real interest rate of slightly below 3%. The relative impatience of borrowers is calibrated at around 1% quarterly. The steady state inflation rate is set to match the annual average of 2%. Physical capital is assumed to depreciate at 2% per quarter and its share in output is set to 0.3, both values being standard in the literature. The share of government purchases in output matches the long-run average of 16.5%. The LTV ratio, share of housing in utility and housing depreciation rate are calibrated to jointly match the following three long-run proportions: the debt-to-GDP ratio of 0.46, the share of residential investment in output of 4.5% and the housing-to-GDP ratio of 1.25.

While calibrating the parameters controlling the degree of heterogeneity between patient and impatient households, we make sure that our choices are consistent with micro data evidence from the Survey of Consumer Finances (SCF) as extracted by Justiniano et al. (2015). More specifically, the share of impatient households (borrowers) is set equal to the share of liquidity constrained consumers (i.e. households with liquid assets worth less than two months of their income), which is 61% according to this data source. If one applies this classification, the SCF implies that, compared to other households, borrowers work on average 8% more hours and their average labor income is 36% lower. We use these two statistics to pin down the share of impatient households in production and the degree of redistribution via the tax system. This calibration also implies that the average total income of borrowers is about 40% of that of savers, which comes very close to 46% according to the SCF.

Another important parameter related to our extension is the lower bound on new loans. As already noted, Justiniano et al. (2015) implicitly set it to zero. Our calibration is based on new mortgage originations in the US. Given the available data presented in Figure 1, a half of the average value of real new loans looks like a plausible floor for this variable so we chose $\bar{l}_t = 0.5l$, where l denotes the steady state level of real loans in our model. This choice also plays very well in the exercise of replicating the US credit boom and crunch (see Section 4.2), which provides additional support to our calibration. Finally, it should be noted that setting the lower bound on new loans above rather than to zero does not alter our results in a qualitative sense. Regarding multi-period loans, we set their average duration at $m = 16$, which allows to match the quarterly loan flow-to-stock ratio in the model steady state and in the data (6.7%).

The parameters controlling real and nominal rigidities, i.e. wage and price markups and stickiness, as well as capital investment adjustment costs are set to standard values assumed in the literature. Finally, the central bank rule is also parameterized in line with the original Taylor rule, except that we allow for some moderate interest rate smoothing.

Estimating models with nonlinearities is a particular challenge. While in theory several techniques are available, in practice they usually suffer from numerical problems and are time consuming. For this reason, in spite of the recent popularity of models with financial frictions, only few have been estimated taking explicitly into account the nonlinearities arising e.g. from collateral constraints binding only occasionally (see Guerrieri and Iacoviello, 2017). Our case is particularly challenging, since the model we consider features two nonlinear constraints. There is, however, a price to be paid – the range of parameters we are able to estimate is relatively narrow.

To be precise, we estimate the autocorrelations and standard deviations of structural shocks (technology, time preference, housing preference and monetary) – this gives seven parameters (the monetary shock is i.i.d.). Fortunately, as shown above, the remaining structural parameters are either well established in the literature or their calibration can be done in line with the data but outside the model. To compute the likelihood, we use the method developed by Guerrieri and Iacoviello (2017) and applied in Bluwstein (2017), which builds upon the piecewise linear solution method and constructs the likelihood function by filtering the errors from the observed data recursively. This method not only allows for parameter estimation, but it also shows us when and which constraint was binding over the time span of our sample.

To estimate the model, we use US quarterly data for real house prices, real GDP, core inflation, and the shadow interest rate for the period 1988q4-2016q2. We detrend the GDP series using an exponential trend and demean all data but the interest rate, for which we use the shadow rate by Wu and Xia (2016) to account for the zero lower bound period. Our prior assumptions are as follows. For all autocorrelations we assume a mean of 0.75, for the standard errors of technology, housing preference and time preference shocks we assume a mean of 0.1, and for the monetary policy shock 0.01. These are standard values in the literature.

Table 2 reports the results of the piecewise linear estimation procedure, in which both constraints were occasionally binding, and for the linear model, which assumes an always binding collateral constraint and never binding lower bound constraint on new loans. The three autoregressive shocks are relatively persistent, with autocorrelation coefficients between 0.72 and 0.98. The standard deviations of shocks seem in line with the values estimated in other papers, ranging from 0.37% for the monetary policy shock to 4.9% in case of the time preference shock. The differences between the nonlinear and linear model are not huge, as it is the case also for instance in Guerrieri and Iacoviello (2017). The differences in parameter estimates reflect the fact that some of the larger variations in the data can now be accounted for due to the inclusion of the two nonlinearities.

Three observations support our claim that the nonlinear estimation should be considered successful. First, as shown on Figure 2, the observable data and the data which the estimated model generates (by feeding the filtered errors which are used to compute the likelihood), match almost perfectly. While this would not be worth mentioning for linear filters, the practice of nonlinear estimation is such that filters are not always successful at replicating observable variables. Second, the posterior standard deviations for all parameters are much narrower than priors. This suggests that the estimation is supported by the data, and not purely driven by our prior assumptions. Third, the marginal data density for the nonlinear model is 1589.3, while that for the linear model is 1580.0. This implies that the data supports the nonlinear model by a posterior odds ratio of more than 11 000 to 1.

Having successfully estimated the model, we can move on to see what it tells us about the behavior of the US mortgage market and the effects of monetary policy under multi-period loans.

4 What does the model tell us about the data (and vice versa)?

As discussed in Section 2, our model features three crucial departures from the benchmark collateral constraint framework of Iacoviello (2005): multi-period loans, lower bound constraint on new lending, and the possibility of the collateral constraint to be slack. Before we discuss how these features work (and in particular how they affect monetary policy transmission), we document their importance in explaining the behavior of the US mortgage market. This section consists of two parts. First, we check what the model says about the periods when the constraints were (or were not) binding. Next we show how the three features help in replicating two key variables that were not treated as observable in estimation: the flow and stock of housing loans.

4.1 The role of nonlinear constraints

The estimation process allows us to check whether and when the two nonlinearities mattered. Figure 4 shows the Lagrange multipliers on the lower bound on new loans and collateral constraint in our estimation sample. Let us start with the lower bound constraint on new borrowing. According to our model, there were two periods when it was binding: 1990-94 and 2008-13 (the multiplier is positive then). Both seem to be associated with credit tightening periods. Figure 3 plots three selected measures of credit market tightness: two discontinued series from the Senior Loan Officer Survey on tightening standards for mortgage loans (total until 2007q1 and prime since 2007q2) and the Chicago Fed National Financial Conditions Credit Subindex. They show that 1990-92 and 2007-10 were the periods of extraordinarily tight credit supply conditions. Our interpretation is that banks sharply tightened credit conditions and, as a consequence, hit the lower bound constraint on new loans (we show in the next subsection that this is also supported by the mortgage flow data).

We now turn to the collateral constraint. Before we do it, one thing needs to be explained. Our modeling assumption was that when the lower bound constraint on new loans binds, the collateral constraint does not bind by construction – otherwise we could face two sharply binding and mutually inconsistent constraints at the same time. Hence we do not evaluate the collateral constraint multiplier dynamics in the period 1990-94 and 2008-13, and accordingly we do not plot it. The remaining periods give the following picture: the constraint was binding between 1994 and 2002. This shows that, in spite of growing house prices, households were still constrained in the first half of the housing market boom. In 2002 the constraint becomes slack and remains so until 2007, which suggests that once house prices increased sufficiently households stopped using their whole borrowing potential to increase leverage. The collateral constraint becomes slack again in the last part of our sample, i.e. after 2013. This is a period when house prices started to grow again while – according to our results – households did not borrow up to their collateral constraint.

4.2 The credit boom and crunch

Now we conduct the following exercise: we use various variants of our model to generate (using the Kalman smoother) two variables crucial from this paper's perspective: the stock and flow of mortgage debt. It should be noted that these variables were not used as observables in the estimation process – this makes our exercise a highly demanding test for the model. The goal is not only to show that our model is able to replicate these series to a surprisingly high degree, but also, that our three key features matter for this success. The figures present the whole sample, but we focus our attention on the most interesting boom-bust period of 1998-2015.

The results for the stock of loans are presented in the upper panel of Figure 5. We start with the baseline one-priod loan framework, i.e. with a permanently binding collateral constraint and no lower bound constraint on new loans, and then consecutively add our new features to document their impact. The solid gray line shows the actual data on real home mortgages. The dashed gray line presents the implied path for this variable obtained from the baseline linear model with single-period loans. In this model, since the collateral constraint holds with equality, loans follow house prices very closely, which translates into a sharp overshooting of debt during the boom and its too dramatic collapse during the bust (as well as another overshooting from 2013 onwards).

As a second step, we add multi-period loans and the lower bound constraint on new borrowing (dotted black line). As explained in Section 5.2, these features work only in interaction – each one introduced separately would produce zero or marginal change. When introduced together, they change the picture substantially as the slope of the bust phase now is less steep and resembles the actual data more closely. As already explained, the lower bound constraint on new loans played an important role in the years 2008-13, as banks could not force households to accelerate loan repayment despite the rapidly falling collateral value. However, during the boom phase this model variant still overestimates the increase in mortgage debt.

We expect that this can be corrected by allowing for our second nonlinearity as we have already shown that during the second half of the boom the collateral constraint relaxed to an extent that households did not necessarily want to exploit it fully. The black dashed line shows the evolution of mortgage debt under this assumption (without the lower bound constraint on new borrowing). As expected, this model variant replicates the boom phase quite well (the collateral constraint is slack during this phase), but fails to explain the slow fall in debt during the bust. Moreover, allowing for the slackness allows to solve the problem of a second boom forming since 2013 – now loans decline as in the data.

Finally, the solid black line represents our complete model – with fixed-rate multi-period loans, occasionally binding credit constraint and the lower bound on new loans. Now the fit is much more in line the with real data. Moreover, one should note that the model-implied peak is very close to the actual one. This is in stark contrast to the linear model, for which mortgage debt just followed the movement of house prices, leading to a much higher (and narrower) peak and an overshooting at the end of the sample. The various models performance can be also evaluated by comparing the mean squared deviations from the data: the nonlinear model's error is only 21% of the linear model's error, highlighting that even if our benchmark model is not perfect, it is much better than the baseline linear case.

Our second variable of interest is the flow of mortgages. While obviously related to the stock, this variable allows us to additionally demonstrate the importance of our modeling assumptions. First of all, it should be noted that for new loans the distinction between single- and multi-period loans is crucial. When loans are single-period, then new loans equal the stock of debt. As a consequence, new loans show no similarity to the data, enough to mention that their steady state ratio to GDP is 45% (compared to 3.5% in the data). Only in the multi-period setting are the new loans generated from the model of a scale comparable to the data. The lower panel of Figure 5 presents two loan flow series generated by various model variants.[4] On the top of this, we plot the actual data on new mortgage originations (gray solid line, source: Mortgage Bankers Association).

First we demonstrate the multi-period, linear case (i.e. with the collateral constraint binding permanently and the lower bound constraint on new loans not binding – gray dashed line). In some periods the simulation diverges sharply from the data. This is in particular the case in 2004-06, when the model predicts a strong expansion in lending, in 2007-09, when the linear model suggests a contraction much sharper than seen in the data, and in the following years, when the model predicts too strong a rebound. The solid black line presents the series generated from our complete nonlinear model. While it is not able to replicate the high-frequency volatility, it captures well the run-up to the boom and the post-crisis credit crunch. In contrast to the linear solution, we avoid both the overshooting of 2004-06, excessive contraction of 2007-09 and the subsequent overreaction of the loan market. There are two short episodes when our nonlinear model fails to replicate the data that well: in 2003 we underpredict the loan

[4] Compared with the stock of loans, we limit the number of plotted lines since new loans are quite volatile and the picture would be hard to read with more series in one figure. The omitted series do not change the general conclusions and are available from the authors upon request.

creation and in 2013 we overpredict it. Nevertheless, the overall match is surprisingly good for a variable that was unobservable in estimation, and the nonlinear model fares much better than the linear one. This can again be seen more formally by comparing the mean squared deviations from the data: their ratio is now even smaller than for the stock and amounts to 16%.

Overall, the goal of this section was to show that our model can tell a consistent and plausible story about the recent developments on the US housing and mortgage markets, and that all the departures from the baseline framework that we consider in the paper are important in this respect. Hence, we believe that our full model has the potential to deliver a more adequate description of the working of stabilization policies that affect these markets. This will be studied in the next section.

5 Implications for monetary policy

We are now ready to show how multi-period loans and the two associated nonlinearities work, and how their presence affects the transmission of monetary policy. Since, as we have shown in the previous section, the degree to which the collateral constraint and lower bound on new loans bind varies over time, the propagation of shocks and policies will exhibit time dependence, and asymmetric responses to positive and negative shocks of the same size can be expected. Moreover, the presence of fixed-rate contracts and of the lower bound on new borrowing, which is more likely to bind when loan duration is high, create interesting interactions between the transmission of shocks and the number of periods for which loans are effectively taken. Our goal is to demonstrate how these features work in our model and show that they can be quantitatively relevant. The time dependence, asymmetry and interactions all essentially apply to any stochastic shocks or policy that one could consider in a model like ours. However, given our paper's focus, we restrict our attention to the transmission of monetary policy innovations.

5.1 Time variation in the monetary transmission mechanism

To demonstrate how, according to our estimated model, the dynamic effects of monetary policy shocks have evolved over time due to the presence of nonlinearities associated with the mortgage market, we proceed as follows. First, we pick four dates in our sample, each representing a different degree of tightness of the collateral constraint and the lower bound on new loans, using the evolution of the Lagrange multipliers presented in Figure 4 as a guideline. The first date is 1995q1, when houses were relatively cheap and the collateral constraint was very tight. The second episode that we focus on is 2006q3, which is roughly in the middle of the period over which the collateral constraint was slack according to our model, and when house prices were at their peak. The third selected date, 2010q1, marks the housing market bust, with steeply falling house prices, tightening credit conditions and a binding lower bound on new loans. During all these periods, the model economy is deeply rooted in a given regime in the sense that monetary policy shocks of standard magnitude are not sufficient to generate a regime switch. This allows us to highlight the time variation of the economy's responses, that depends on which constraint binds or not, rather than the asymmetries associated with moving from one regime to another. The latter effects are illustrated using the fourth date, 2002q1, around which the model sees the mortgage market being close to the lower bound on new borrowing so that a monetary policy tightening results in hitting this constraint while a monetary easing easing keeps the regime unchanged.

We start with presenting the reactions of our model economy to a standard monetary policy shock. These are calculated by initializing the model from the values of the state variables identified on a given date during the estimation procedure by the Kalman filter, and simulating it forward, either assuming no further shocks or a one standard deviation innovation to the monetary policy feedback rule. The differences between these two paths for the four selected starting points are plotted in Figure 6. Let us first concentrate on its left column which documents the reactions to a contractionary shock.

It is convenient to first discuss the responses for 2006q3, i.e. when the collateral constraint was not binding. The reactions of output and inflation are in line with what is known from the literature on how the economy responds to a monetary tightening – both variables fall and then gradually return to the steady state. Since the higher cost of credit acts as a negative income shock for impatient households and a positive one for patient agents, both types smooth their consumption by increasing borrowing or saving, respectively. As a result, and also due to the working of the Fisherian debt deflation channel, total real debt in the economy goes up. This variable responds differently when the collateral constraint is binding, like in 1995q1. Since a monetary policy tightening depresses house prices, and hence the value of collateral that can be used to secure loans, borrowers become even more financially constrained, so less new loans are taken and the stock of debt falls. This acts as a financial accelerator, amplifying the negative response of output. If borrowers are constrained, but the amount of new loans rests on its lower bound (which is how our model interprets the mortgage market stance in 2010q1), this variable does not move until the constraint becomes slack. As a result, real debt barely changes as its increase only reflects the debt deflation effect, and the contraction in output is only slightly deeper compared to the episodes during which the collateral constraint was not binding.

Let us now discuss asymmetries and, to this end, compare the left and right column of Figure 6, where the latter shows reactions to a monetary expansion. For the three starting points described above, the responses are symmetric as the considered monetary shocks are not large enough to trigger a regime switch. This is not the case for our fourth date, 2002q1, at which only the collateral constraint is binding, but new loans are close to their lower bound. As a result, a monetary easing leads to an expansion in output, inflation and debt that is very similar to that obtained for 1995q1. In contrast, as depicted in the left column, after an increase in the policy rate, new loans hit the lower bound, which effectively limits their adjustment for the first two periods after the shock. As a result, debt responds with a delay, and so does output, reaching its trough only after a year rather than on impact.

Overall, the presented simulations show how the effects of monetary policy may depend on the momentum of the housing cycle as the latter affects the degree to which the financial accelerator mechanism amplifies the initial impulse. The occasionally binding nature of the constraints associated with the mortgage market can also generate significant asymmetries, concerning both the magnitude and timing of responses to positive and negative shocks.

5.2 Interactions between mortgage market nonlinearities and loan maturity

As we already have stressed, the three features of mortgage markets that we consider, i.e. multiperiodicity of loans, the occasionally binding nature of collateral constraints and the existence of a lower bound for new loans, are not only important stand-alone modifications to the standard macroeconomic setup, but can also enter into powerful interactions. In particular, the distinction between fixed and adjustable-rate loans does not make sense if contracts are single-period. Moreover, as explained below, the lower bound on new loans binds easier for longer loan maturities. In this section we take a closer look at these two particular interactions by demonstrating how the strength and asymmetries in the monetary policy transmission depend on debt duration that in our framework is represented by parameter $\boldsymbol{m}$.[5]

To this end, in Figure 7 we plot the peak and trough responses of output and inflation to negative and positive monetary policy shocks as a function of loan maturity. We consider shocks of one and two standard deviations. While calculating the responses, we assume that the economy is initially in the steady state equilibrium. Naturally, given the time dependence arising from the nonlinearities included in our model, the outcomes would be different if we considered alternative initial conditions. However, the steady state is a natural benchmark and sufficient to demonstrate our main point,

[5]In the discussion presented in this section, we abstract away from the asymmetries associated with possible slackness in the collateral constraint as these have been already discussed e.g. by Guerrieri and Iacoviello (2017), and they do not enter into interesting interactions with loan maturity.

which is the interaction of the strength of the responses with loan maturity.

The following observations can be made. First of all, the effect of monetary policy clearly decreases with loan maturity. This happens even if we ignore the occasionally binding nature of the constraints that result in discontinuities observed in the figure, and which we discuss later. The reason is that, under fixed-rate multi-period contracts, a change in the policy rate affects only the cost of newly granted loans. Therefore, the higher is the loan duration, the lower is the proportion of total debt to which new financial terms apply, and the less sensitive are borrowers to monetary easing or tightening. These results apply to both the maximum response, which is plotted in the figure, as well as the cumulative response, indicating that even over a longer time horizon, monetary policy will always be less effective under higher loan duration. Note that this experiment can also be interpreted as documenting the lower effectiveness of monetary policy under fixed versus variable rate loans, as the latter are equivalent to single period loans if the lower bound on new borrowing does not bind.

The second observation that one can draw from Figure 7 is the presence of discontinuities for contractionary shocks. They are associated with the lower bound on new loans and, if loan duration or the size of shocks is sufficiently large, result in asymmetries in responses to positive and negative shocks. To see why loan duration matters here, note that the larger it is, the smaller the steady state share of new loans in total debt, see equation (3). Note that we calibrate the lower bound on new borrowing as half of its steady state value. As a result, the absolute magnitude by which new loans can fall before hitting their lower bound also decreases in m. Consequently, for a given adjustment in total debt implied by the collateral constraint, the lower bound on new loans is more likely to be hit if the contract maturity is higher. Since our simulations start from the steady state, in which the collateral constraint is binding and the lower bound on new borrowing is not, the latter nonlinearity may be activated only in experiments featuring a decrease in debt. Hence, the effects of a monetary tightening on total lending might be smaller compared to a monetary easing of the same scale. As our simulations show, this asymmetry is much more relevant for output than for inflation.

All this discussion clearly indicates that the average mortgage loan maturity is an important parameter determining the strength and asymmetries in the monetary policy transmission mechanism.

6 Conclusions

In this paper we modify an otherwise standard DSGE model with housing and financial intermediaries in order to take into account some typical characteristics of residential mortgage markets – those that empirical studies have found to be relevant in many dimensions, and that are largely ignored in the theoretical literature. The aim of considering these modifications is to evaluate to what extent they affect the transmission mechanism of monetary policy. The main non-standard component that we focus on is the introduction of multi-period loan contracts, as well as two features that make our model more realistic: a lower bound constraint on new loans and the possibility that the collateral constraint might become slack.

We first estimate the model using nonlinear Bayesian estimation techniques and demonstrate that all of these modifications are crucial in making our framework consistent with housing market developments during the recent boom-bust cycle in the US. In particular, we document that the nonlinear setting is much better supported by the data. We also show that our estimated model with multiperiod loans and occasionally binding constraints does (in contrast to the standard, linear model) a very good job in matching two key variables that we chose to be unobserved in the estimation process: the stock of debt and new mortgage originations.

As regards monetary policy transmission, we confirm the conclusion from the empirical literature that monetary policy is less effective with fixed-rate mortgages than with variable-rate ones. Furthermore, we show that its transmission weakens in average debt maturity, can exhibit substantial asymmetries and depends on the momentum of the housing cycle.

We believe that our results can be helpful in understanding the implications of the observed cross-country heterogeneity in the mortgage market design for the monetary policy transmission mechanism. Moreover, it is important to stress that the highlighted time dependence and possible asymmetries are not restricted to the effects of monetary shocks. In particular, the nonlinearities associated with the mortgage market may also limit the effectiveness of macroprudential policy. We leave this issue for possible future research.

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Tables and figures

Table 1: Calibration

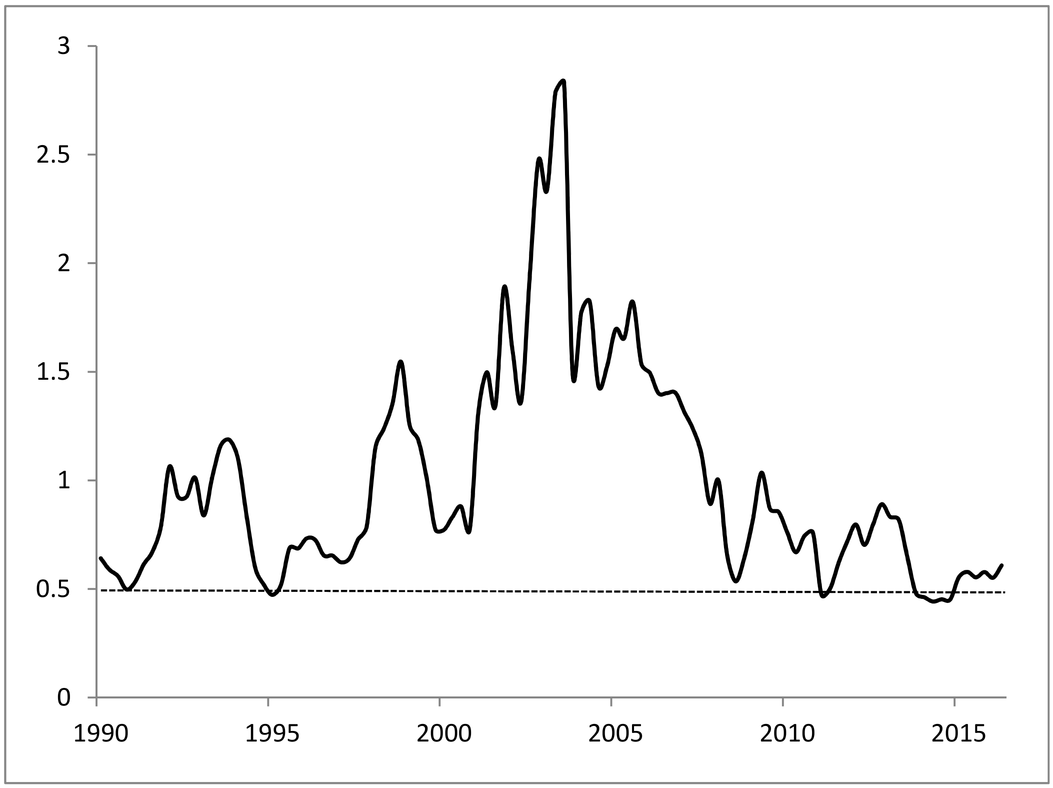
Parameter	Value	Description
β_P	0.993	Discount factor, patient HHs
β_I	0.983	Discount factor, impatient HHs
δ_h	0.009	Housing stock depreciation rate
δ_k	0.02	Capital stock depreciation rate
ω	0.61	Share of impatient HHs in population
γ	0.5	Share of impatient HHs in production
A	0.138	Steady state weight on housing in utility
σ_n	1	Inverse of Frisch elasticity of labor supply
μ_w	1.2	Steady state wage markup
θ_w	0.75	Calvo probability for wages
μ	1.2	Steady state product markup
θ	0.75	Calvo probability for prices
α	0.3	Output elasticity with respect to physical capital
κ	5	Capital investment adjustment cost
g_y	0.165	Share of government spending in output
τ	-0.165	Share of taxes levied on impatient HHs
ϑ	0.83	LTV ratio
π	1.005	Steady state inflation
γ_R	0.9	Interest rate smoothing in monetary policy rule
γ_π	1.5	Response to inflation in monetary policy rule
γ_y	0.5	Response to output in monetary policy rule

Table 2: Estimated Parameters

Shock	Prior		Posterior (linear)		Posterior (OccBin)	
	Mean	St. dev.	Median	St. dev.	Median	St. dev.
			AR coefficients			
Housing preference	0.75	0.1	0.9842	0.0040	0.9813	0.0009
Time preference	0.75	0.1	0.8774	0.0090	0.8840	0.0019
Technology	0.75	0.1	0.7303	0.0227	0.7242	0.0092
			Standard deviations			
Housing preference	0.1	5	0.0447	0.0061	0.0419	0.0010
Monetary	0.01	0.5	0.0023	0.0002	0.0037	0.0004
Time preference	0.1	1	0.0475	0.0033	0.0491	0.0005
Technology	0.1	1	0.0124	0.0005	0.0129	0.0005

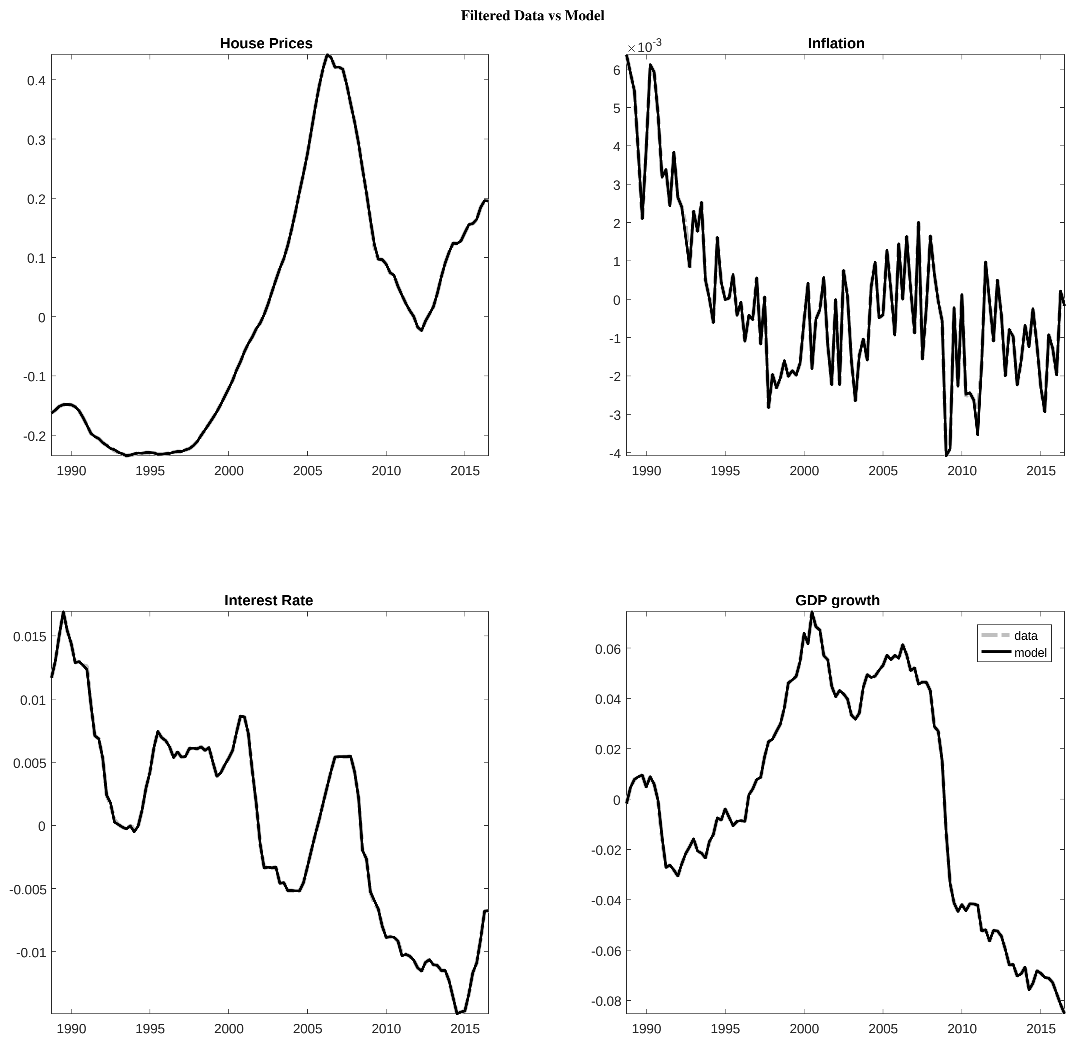
Note: The posterior statistics are based on 10 000 draws from the random walk Metropolis-Hastings algorithm. Starting values were chosen based on the estimated parameters of the model with a permanently binding borrowing constraint. The first 30% of draws are discarded as burn-in.

Figure 1: New mortgage originations



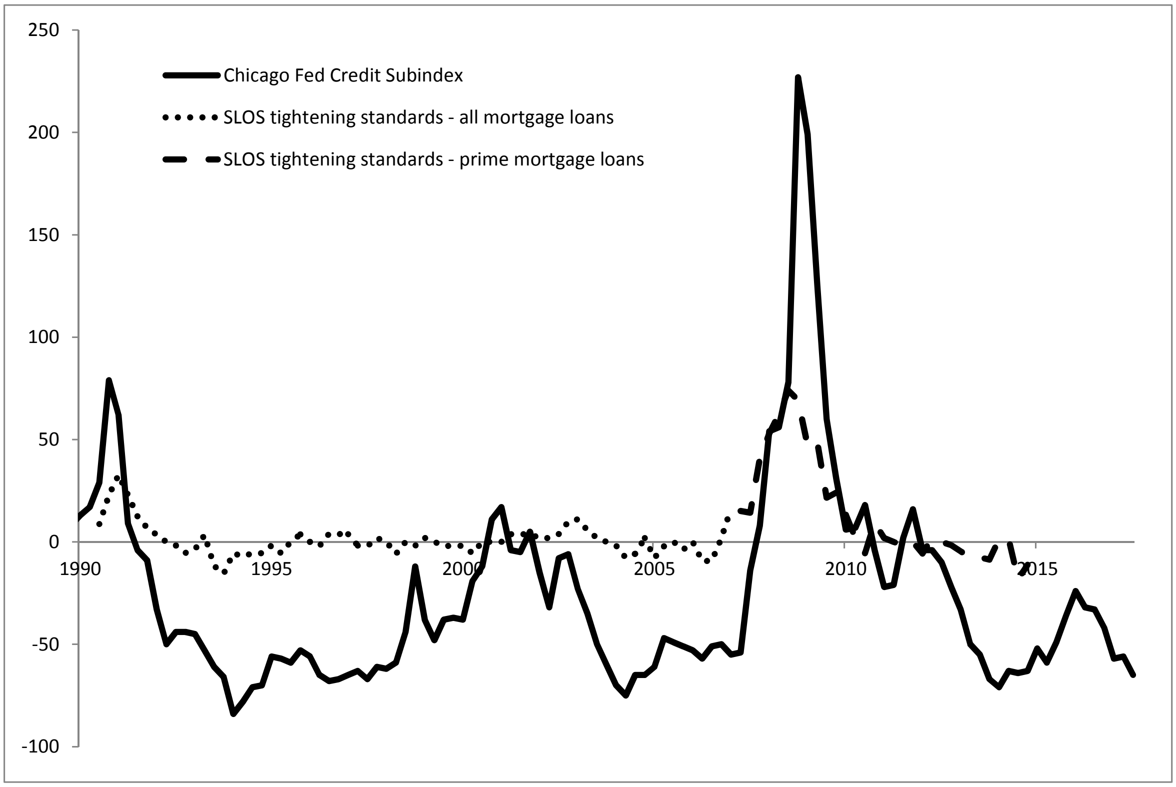
Note: This chart plots mortgage originations (new loans) in the US (source: Federal Housing Finance Agency data on mortgage originations for 1-4 family homes), CPI deflated and linearly detrended with the average real GDP growth rate over the period 1975-2016. Period average = 1. The dotted line shows our choice of the lower bound on new loans.

Figure 2: Real data versus simulated data from estimated model



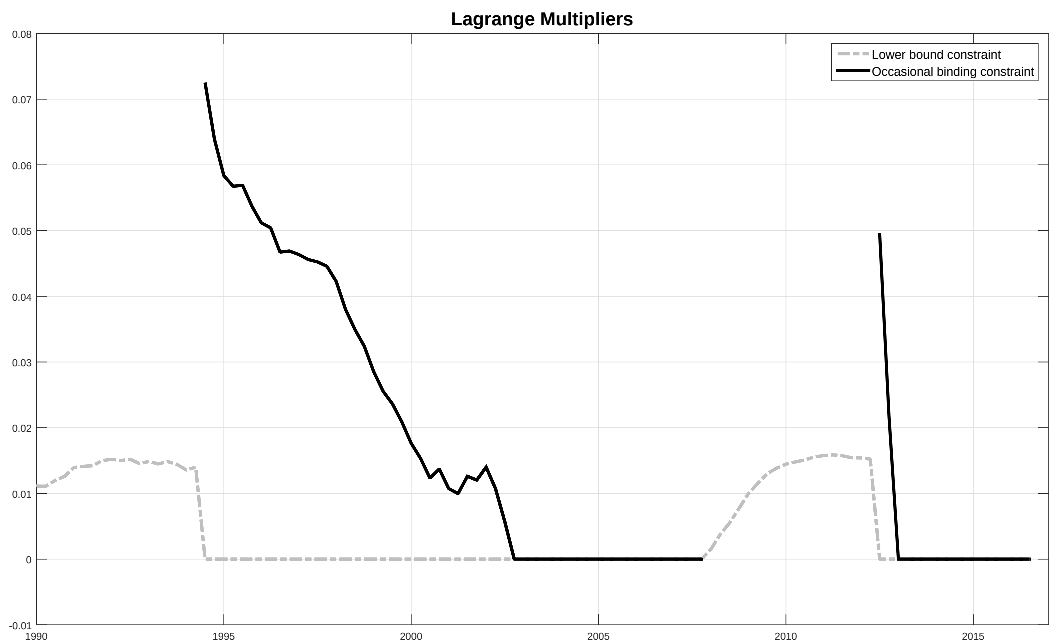
Note: The dashed line depicts real data used for the estimation. The solid line shows how well the model fits the data.The magnitude of the largest difference between the original sample and the synthetic sample is 0.0037 which indicates that the estimated parameters generate a good fit for the data.

Figure 3: Credit standards



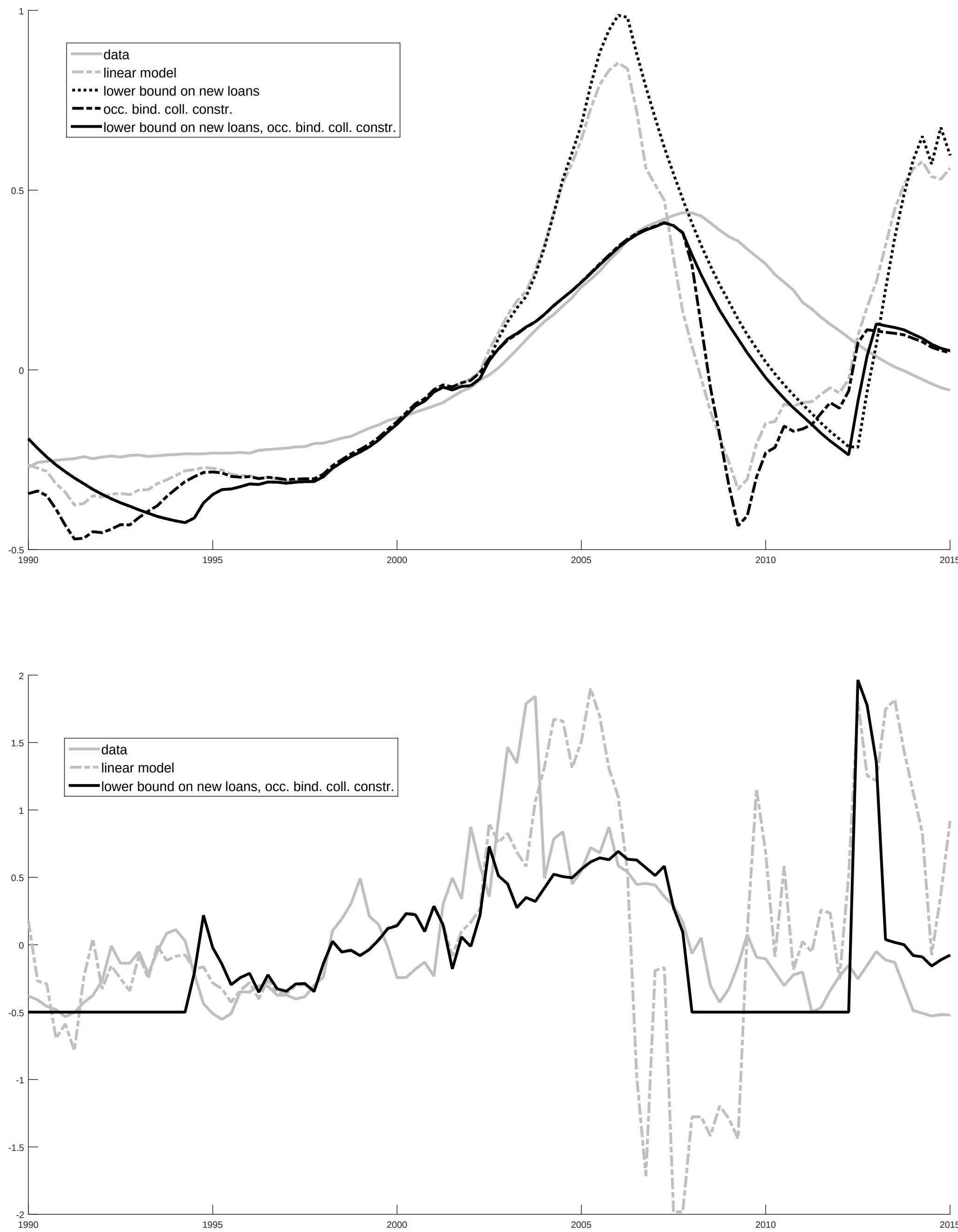
Note: The two series from the Senior Loan Officer Survey (SLOS) show the net percentage of banks tightening standards for mortgage loans (total until 1Q2007 and prime since 2Q2007). Data is available only until 4Q2014. The third series is the Chicago Fed National Financial Conditions Credit Subindex.

Figure 4: Lagrange Multipliers on Borrowing and Lower Bound Constraint on New Borrowing



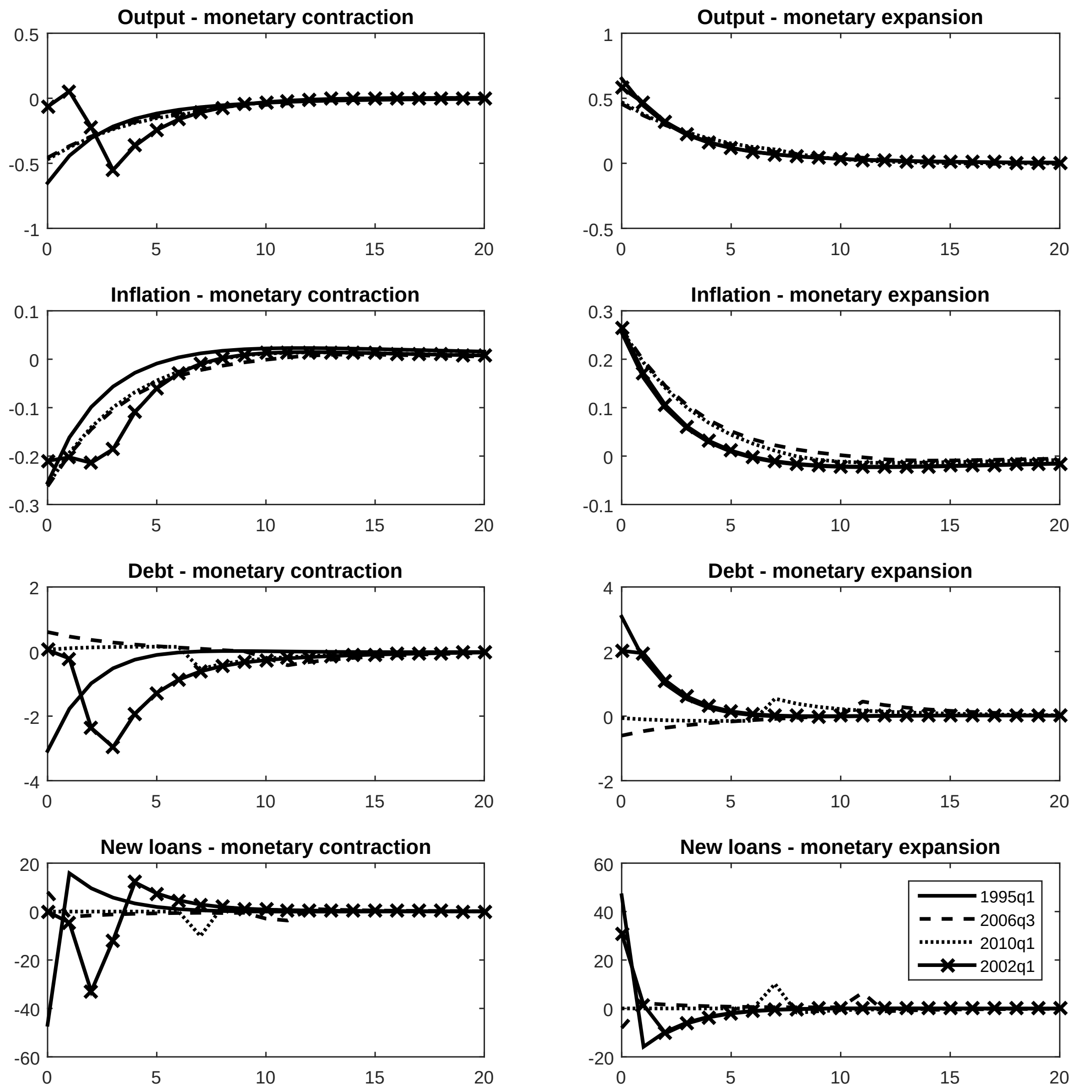
Note: The borrowing constraint is non-binding, when its Lagrange multiplier is zero, and the lower bound on new loans binds, when its Lagrange multiplier is non-zero. In periods when the lower bound constraint on new loans was binding the collateral constraint has been relaxed by construction, for this reason we do not plot it.

Figure 5: Simulated and historical mortgage debt (stock and flow)



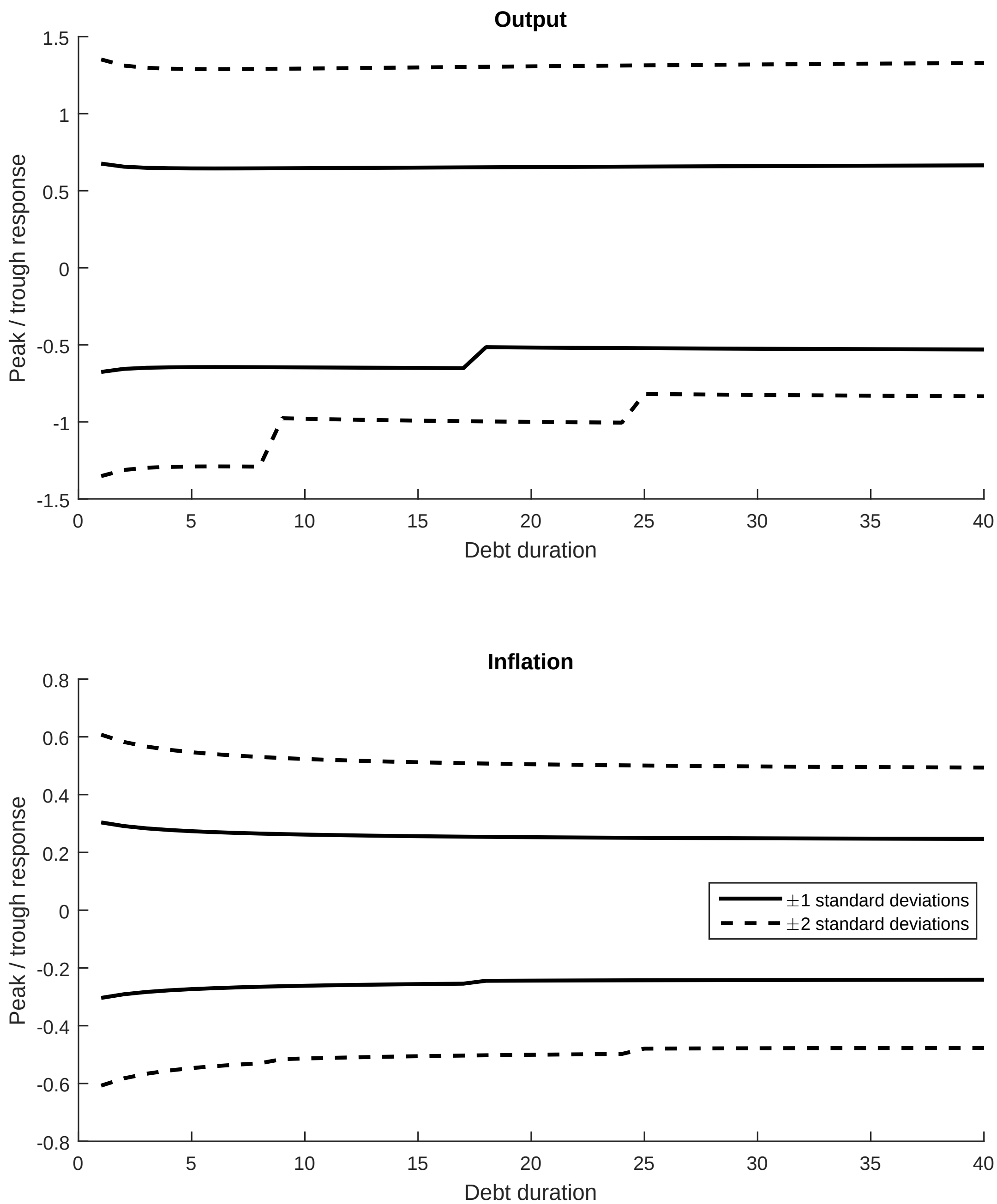
Note: The upper panel plots the evolution of the stock of real mortgage debt in the US (source: US Flow of funds (Z1); home mortgages to households and nonprofit organizations). The lower panel plots the evolution of the real, new mortgage originations in the US (source: Mortgage Bankers Association). Both series were linearly detrended with the average real GDP growth rate over the period 1975-2016 and are presented in percent deviation from mean. Additionally, we plot paths for these variables implied by different model variants. The model-based paths are generated by feeding the filtered errors into the nonlinearly estimated model.

Figure 6: Reaction to a contractionary and expansionary monetary policy shock



Note: The figure plots the responses to a typical contractionary (left column) and expansionary (right column) monetary policy shock at four dates in our sample. All responses are in percent deviations from the baseline, inflation is annualized.

Figure 7: Loan maturity and asymmetric transmission of monetary policy shocks



Note: Maximum responses of output and inflation to positive (lines below zero) and negative (lines above zero) interest rate shocks of different size (1 std - solid lines, 2 std - dashed lines), starting from the non-stochastic steady state. All responses are in percent deviations from the steady state, annualized.

Appendix

A List of model equations

The following equations describe the equilibrium in our model. Small letters for variables defined in the main text with capital letters are used to indicate real quantities or prices, defined by dividing the nominal values by the aggregate price level P_t. The Lagrange multipliers associated with the collateral constraint and lower bound on new loans are denoted by $\lambda_{2,t}$ and $\lambda_{3,t}$, respectively.

Marginal utility of consumption (for $i = \{I, P\}$)

$$u'_{i,t} = \frac{\varepsilon_{u,t}}{c_{i,t}} \tag{A.1}$$

Impatient households' budget constraint

$$c_{I,t} + p_{h,t}(h_{I,t} - (1-\delta_h)h_{I,t-1}) + \frac{\phi_{t-1}}{\pi_t} + \frac{s_{t-1}}{\pi_t} = w_t n_{I,t} + s_t - \frac{\tau}{\omega} g_y y_t \tag{A.2}$$

Debt accumulation

$$s_t = l_t + (1 - \frac{1}{m})\frac{s_{t-1}}{\pi_t} \tag{A.3}$$

Promised interest payments

$$\phi_t = (R_{h,t} - 1)l_t + (1 - \frac{1}{m})\frac{\phi_{t-1}}{\pi_t} \tag{A.4}$$

Demand for loans by impatient households

$$u'_{I,t} = \beta_I \mathbb{E}_t \left\{ \frac{u'_{I,t+1}}{\pi_{t+1}} \right\} + \lambda_{2,t} R_t + \psi^I_{I,t}(R_{h,t} - 1) - \beta_I (1 - \frac{1}{m}) \mathbb{E}_t \left\{ \frac{\psi_{I,t+1}}{\pi_{t+1}} (R_{h,t+1} - 1) \right\} + \lambda_{3,t} \tag{A.5}$$

$$\psi^I_t = \beta_I \mathbb{E}_t \left\{ \frac{u^I_{c,t+1}}{\pi_{t+1}} \right\} + \beta_I (1 - \frac{1}{m}) \mathbb{E}_t \left\{ \frac{\psi^I_{t+1}}{\pi_{t+1}} \right\} \tag{A.6}$$

Lower bound constraint on new loans

$$l_t \geq \bar{l} \tag{A.7}$$

Collateral constraint

$$R_t s_t \leq \vartheta(1-\delta_h)\mathbb{E}_t\left\{p_{h,t+1} h_{I,t} \pi_{t+1}\right\} \qquad \text{if} \quad \lambda_{3,t} = 0 \tag{A.8}$$

$$\lambda_{2,t} = 0 \qquad \text{if} \quad \lambda_{3,t} > 0 \tag{A.9}$$

Supply of deposits by patient households

$$u'_{P,t} = \beta_P \mathbb{E}_t\left\{R_t \frac{u'_{P,t+1}}{\pi_{t+1}}\right\} \tag{A.10}$$

Housing Euler equations

$$A\frac{\varepsilon_{h,t}}{h_{I,t}} + \beta_I(1-\delta_h)\mathbb{E}_t\left\{u'_{I,t+1} p_{h,t+1}\right\} + \vartheta(1-\delta_h)\lambda_{2,t}\mathbb{E}_t\left\{p_{h,t+1}\pi_{t+1}\right\} = u'_{I,t} p_{h,t} \tag{A.11}$$

$$A\frac{\varepsilon_{h,t}}{h_{P,t}} + \beta_P(1-\delta_h)\mathbb{E}_t\left\{u'_{P,t+1} p_{h,t+1}\right\} = u'_{P,t} p_{h,t} \tag{A.12}$$

Banks' optimality conditions

$$u'_{P,t} = \beta_P \mathbb{E}_t\left\{\frac{u'_{P,t+1}}{\pi_{t+1}}\right\} + \psi_{P,t}(R_{h,t}-1) - \beta_P(1-\frac{1}{m})\mathbb{E}_t\left\{\frac{\psi_{P,t+1}}{\pi_{t+1}}(R_{h,t+1}-1)\right\} \tag{A.13}$$

$$\psi_{P,t} = \beta_P \mathbb{E}_t\left\{\frac{u'_{P,t+1}}{\pi_{t+1}}\right\} + \beta_P(1-\frac{1}{m})\mathbb{E}_t\left\{\frac{\psi_{P,t+1}}{\pi_{t+1}}\right\} \tag{A.14}$$

Capital accumulation

$$k_t = (1-\delta_k)k_{t-1} + \left(1-\Gamma\left(\frac{i_{k,t}}{i_{k,t-1}}\right)\right)i_{k,t} \tag{A.15}$$

Demand for capital

$$u'_{P,t} p_{k,t} = \beta_P \mathbb{E}_t\left\{u'_{P,t+1}\left[(1-\delta_k)p_{k,t+1} + r_{k,t+1}\right]\right\} \tag{A.16}$$

Investment demand

$$1 = p_{k,t}\left[1-\Gamma\left(\frac{i_{k,t}}{i_{k,t-1}}\right)-\Gamma'\left(\frac{i_{k,t}}{i_{k,t-1}}\right)\frac{i_{k,t}}{i_{k,t-1}}\right]+\beta_P\mathbb{E}_t\left\{\frac{u'_{P,t+1}}{u'_{P,t}}p_{k,t+1}\Gamma'\left(\frac{i_{k,t+1}}{i_{k,t}}\right)\frac{i^2_{k,t+1}}{i^2_{k,t}}\right\} \tag{A.17}$$

Wages by household type (for $i = \{I, P\}$)

$$w_{i,t} = \left[\theta_w\left(\frac{w_{i,t-1}\pi}{\pi_t}\right)^{\frac{1}{1-\mu_w}}+(1-\theta_w)\tilde{w}_{i,t}^{\frac{1}{1-\mu_w}}\right]^{1-\mu_w} \tag{A.18}$$

Optimal reset wage (for $i = \{I, P\}$)

$$\tilde{w}_{i,t}^{1+\sigma_n\frac{\mu_w}{\mu_w-1}} = \frac{\Omega^w_{i,t}}{\Upsilon^w_{i,t}} \tag{A.19}$$

$$\Omega^w_{i,t} = \mu_w w_{i,t}^{\frac{\mu_w}{\mu_w-1}(1+\sigma_n)}n_{i,t}^{1+\sigma_n}+\beta_i\theta_w\mathbb{E}_t\left\{\left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu_w}{1-\mu_w}(1+\sigma_n)}\Omega^w_{i,t+1}\right]\right\} \tag{A.20}$$

$$\Upsilon^w_{i,t} = u'_{i,t}w_{i,t}^{\frac{\mu_w}{\mu_{w-1}}}n_{i,t}+\beta_i\theta_w\mathbb{E}_t\left\{\left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{1}{1-\mu_w}}\Upsilon^w_{i,t+1}\right\} \tag{A.21}$$

Average wage

$$w_t = \left(\frac{w_{I,t}}{\gamma}\right)^{\gamma}\left(\frac{w_{P,t}}{1-\gamma}\right)^{1-\gamma} \tag{A.22}$$

Labor demand

$$n_{I,t} = \frac{\gamma}{\omega}\frac{w_t}{w_{I,t}}n_t \qquad n_{P,t} = \frac{1-\gamma}{1-\omega}\frac{w_t}{w_{P,t}}n_t \tag{A.23}$$

Aggregate inflation

$$1 = \theta\left(\frac{\pi}{\pi_t}\right)^{\frac{1}{1-\mu}}+(1-\theta)\tilde{p}_t^{\frac{1}{1-\mu}} \tag{A.24}$$

Optimal reset price

$$\tilde{p}_t = \mu\frac{\Omega_t}{\Upsilon_t} \tag{A.25}$$

$$\Omega_t = u'_{P,t}mc_t y_t+\beta_P\theta\mathbb{E}_t\left\{\left(\frac{\pi}{\pi_{t+1}}\right)^{\frac{\mu}{1-\mu}}\Omega_{t+1}\right\} \tag{A.26}$$

$$\Upsilon_t = u'_{P,t} y_t + \beta_P \theta \mathbb{E}_t \left\{ \left(\frac{\pi}{\pi_{t+1}} \right)^{\frac{1}{1-\mu}} \Upsilon_{t+1} \right\} \tag{A.27}$$

Marginal cost

$$mc_t = \frac{1}{\varepsilon_{z,t}} \left(\frac{r_{k,t}}{\alpha} \right)^{\alpha} \left(\frac{w_t}{1-\alpha} \right)^{1-\alpha} \tag{A.28}$$

Optimal factor proportions

$$\frac{r_{k,t}}{w_t} = \frac{\alpha}{1-\alpha} \frac{n_t}{k_{t-1}} \tag{A.29}$$

Monetary policy rule

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\gamma_R} \left[\left(\frac{\pi_t}{\pi} \right)^{\gamma_\pi} \left(\frac{y_t}{y} \right)^{\gamma_y} \right]^{1-\gamma_R} \varepsilon_{R,t} \tag{A.30}$$

Housing market clearing

$$h = \omega h_{I,t} + (1-\omega) h_{P,t} \tag{A.31}$$

Aggregate resource constraint

$$(1-g_y) y_t = \omega c_{I,t} + (1-\omega) c_{P,t} + i_{k,t} + \delta_h h \tag{A.32}$$

Aggregate production function

$$y_t \Delta_t = \varepsilon_{z,t} k_{t-1}^{\alpha} n_t^{1-\alpha} \tag{A.33}$$

Price dispersion

$$\Delta_t = (1-\theta) \tilde{p}_t^{\frac{\mu}{1-\mu}} + \theta \left(\frac{\pi}{\pi_t} \right)^{\frac{\mu}{1-\mu}} \Delta_{t-1} \tag{A.34}$$