# The macroeconomic effects of temporary and persistent changes in the monetary policy rate*

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**Abstract**

New-Keynesian models abstract from long-term securities and thus from the real effects of long-term nominal interest rates. Some economic decisions, however, depend on long rates and the central bank policy rate contains a persistent component affecting long rates. We extend the canonical New-Keynesian model by introducing long-term nominal mortgages, thus giving both ends of the yield curve roles in the monetary transmission mechanism. We find that nominal shocks of different persistence have even qualitatively different real effects, are transmitted through different rigidities (sticky prices vs. mortgages), and there is little interaction between the two rigidities.

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**Keywords:** Mortgages, sticky prices, monetary policy, yield curve.

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# 1 Introduction

Central banks choose the short-term nominal interest rate to control inflation and smooth out output fluctuations. Many decisions in the real economy, however, depend on interest rates on assets and liabilities of longer maturities than the maturity of the short-term debt linked to the central bank policy rate. Indeed, in the minds of policy makers, the short rate is often viewed only as an instrument to eventually affect long rates. From a purely empirical perspective, movements in the short rate share a large common component with movements in the long rate. The New-Keynesian model—a widely-used workhorse in the analysis of monetary policy—however, abstracts from any explicit role of long-term assets and liabilities and thus from the real effects of the long end of the nominal yield curve.[1]

To address this limitation, we introduce long-term nominal debt, specifically mortgage debt, into a New-Keynesian model. In the extended model, homeowners purchase housing with mortgages, provided by mortgage investors as a part of their broader saving decision. As a consequence, both short and long rates affect household decisions in a nontrivial way. We then ask the following questions about the monetary transmission mechanism: (i) how do the real effects of shocks to the slope of the nominal yield curve—i.e., changes mainly in the short rate—differ from the real effects of shocks to the level of the yield curve—i.e., changes in the common component of short and long rates? (ii) which rigidity—sticky prices or long-term nominal mortgages—is more important for the transmission of the two types of shocks? and (iii) what, if any, is the interaction between the two rigidities in transmitting the shocks?

Our focus on mortgages, as a form of long-term nominal debt, is motivated by the following observations. First, the size of mortgage debt in many developed economies is large, equivalent to 70% of annual GDP, which is comparable to the size of government debt (OECD avarage for 2009, International Monetary Fund, 2011, Chapter 3). Second, mortgages are the main financial liability of the household sector and the purchase of a house, the main asset for most households, is in

[1]The role of long-term interest rates in New-Keynesian models is implicit, in the sense that a short-term bond is traded every period and forward-looking agents care about the interest rate on that bond in the future.

many countries highly dependent on mortgage financing (Campbell and Cocco, 2003).[2] Third, mortgage payments—interest and amortization—account for a sizable fraction of household expenditures. For example, in the United States over the past forty years, mortgage payments were, on average, equivalent to 15 to 20% of homeowners' income, depending on the data used; similar magnitudes are observed also for other countries (Garriga, Kydland and Šustek, 2017, and the references therin). And fourth, mortgage loans have one of the longest terms in the economy, with the typical term being 15-30 years (International Monetary Fund, 2011).

A natural complication arising with long-term debt is the need to distinguish between new loans (flow) and outstanding debt (stock). The effects of monetary policy, both direct and general equilibrium, on the affordability of new loans may be very different from the effects on the affordability of outstanding debt.[3] A further issue, specific to mortgages, is that the form of mortgage contracts differs across countries. For the monetary transmission mechanism, a key distinction is between fixed- and adjustable-rate mortgages, FRM vs. ARM. In the United States, for instance, the typical mortgage is a 30-year FRM (i.e., the nominal mortgage interest rate is fixed for the entire term of the loan, 30 years). Similar loans are also common in Belgium, Denmark, France, Germany, and the Netherlands. In other countries, however, the typical contract is a variant of an ARM (i.e., the mortgage interest rate adjusts more or less in line with the central bank policy rate). We do not focus on any specific country and, instead, consider each mortgage type within a common quantitative framework.[4]

To illustrate the differential direct effects of monetary policy, Figure 1 plots the movements in mortgage rates (aggregate averages) in a number of euro area countries around the time of the ECB rate cuts in 2008. While interest rates

[2] Long-term debt is a much less important source of investment funds for the nonfinancial corporate sector (e.g., Rajan and Zingales, 1995).

[3] By direct effects we mean changes in mortgage interest rates, by general equilibrium effects any other adjustments in the economy, especially of inflation and household income.

[4] Cross-country differences in mortgage contracts, and the relative shares of FRMs and ARMs, are discussed by, e.g., Scanlon and Whitehead (2004), Green and Wachter (2005), European Mortgage Federation (2012), Campbell (2013), and Badarinza, Campbell and Ramadorai (2016). A theory of such differences, however, still needs to be developed (Campbell, 2013).

on new mortgage loans in ARM countries declined immediately and by almost as much as the ECB rate, the decline in interest rates on new mortgages in FRM countries was smaller and more gradual. A more dramatic difference is observed in the case of outstanding debt. In ARM countries, the interest rate on outstanding debt declined again by almost as much as the ECB rate, whereas in FRM countries it remained essentially unchanged.[5]

As a FRM is a long-term debt contract with a fixed interest rate, the FRM rate on new loans is closely related to the long end of the yield curve. By the expectations hypothesis, the FRM rate is thus related to expected future policy rates. Other things equal, changes in the policy rate that are perceived to be persistent have a larger effect on the FRM rate than changes that are perceived to be temporary. In the ARM case, the role of the yield curve is more subtle. Like a FRM, an ARM is a long-term loan. Its affordability to forward-looking homeowners thus depends on the expected path of the ARM rate over the life of the loan, not just on the current ARM rate. The expected future path of policy rates, and in this sense the yield curve, therefore matters again. These effects affect in our model household decisions above and beyond the standard New-Keynesian channel, operating through the interest rate on a one-period bond.[6]

In a New-Keynesian environment, expected future monetary policy affects the equilibrium also through firms, which care about expected future inflation when setting current prices. The price-setting behavior has implications for aggregate output, inflation, and the real interest rate. With mortgages, there are also consequences for the real value of mortgage payments on outstanding debt (and on new loans in expectations), and the magnitude of those payments in relation to households' income.

In this paper we study such interactions between the New-Keynesian frictions

[5]In principle, mortgages can be pre-paid or refinanced. The extent to which this is legally or economically feasible, however, varies across countries (Scanlon and Whitehead, 2004; Green and Wachter, 2005; European Mortgage Federation, 2012; Badarinza et al., 2016). The lack of responses of the interest rates on FRM outstanding debt in Figure 1 suggests that in the FRM euro area countries little refinancing took place in response to the ECB rate cuts.

[6]At a technical level, in the case of mortgages (both FRM and ARM), one of the equilibrium Euler equations contains the entire expected future path of the short rate. In contrast, in the standard model only the current short rate shows up in an Euler equation, even though current consumption can be expressed as a function of the future path of the short rate once a sequence of the Euler equations is substituted out.

and mortgages in the context of the classic question of how purely nominal shocks, in our case to the short-term nominal interest rate, transmit into the real economy. Following the New-Keynesian literature, a temporary shock, affecting mainly the short rate, is modeled as a standard monetary policy shock in a Taylor rule and its autocorrelation is calibrated to generate the typical VAR responses documented in the empirical literature (e.g., Bernanke and Gertler, 1995). A persistent shock, affecting both short and long rates, is modeled as a stochastic inflation target, as in the macro-finance literature (e.g., Gurkaynak, Sack and Swanson, 2005). In line with this literature, its autocorrelation is calibrated to the autocorrelation of the common component of short and long rates, extracted from the empirical yield curve.[7]

The calibrated model yields the following answers to our three questions; we consequently provide analytical explanations of the findings. First, the temporary shock has mainly aggregate real effects. A positive shock reduces output and all of its components, including consumption of both mortgage borrowers and lenders and investment in housing and nonhousing capital. The real effects are, however, short-lived. The persistent shock has small aggregate effects but large redistributive effects between the two agent types, which are highly persistent. Second, the temporary shock is transmitted through sticky prices, whereas the persistent shock is transmitted mainly through mortgages. And third, related to the second result, there is little interaction between the two rigidities in the transmission of the shocks, at least for their calibrated persistence.[8] The three results hold regardless of whether FRM or ARM contracts are considered, although there are differences in the actual responses of the economy to the persistent shock under the two contracts (by an implication of the second result, the responses to the temporary shock are the same under FRM and ARM). Where

[7]In this paper, we abstract from any other factors affecting the yield curve, such as movements in term premia, shocks leading to variations in the natural real rate, as well as from factors affecting the spread between mortgage rates and government bond yields of comparable maturities. Some of these factors may also be affected by monetary policy (Gertler and Karadi, 2015).

[8]For comparison, we experiment also with persistence of the shocks that lies in-between the two baseline cases and with movements in the inflation target that are triggered by real shocks and standard monetary policy shocks, as in Gurkaynak et al. (2005), Ireland (2007), and Rudebusch and Swanson (2012).

possible, we connect the findings with the relevant empirical studies.

The paper is broadly related to two agendas. First, to a literature combining New-Keynesian and term structure models; e.g., Hordahl, Tristani and Vestin (2006), Rudebusch and Wu (2008), Bekaert, Cho and Moreno (2010), and Doh (2011). The aim of these studies is to provide macroeconomic underpinnings to the latent factors in the reduced-form affine term structure models. In these papers, the equilibrium laws of motion of the macro model enter the yield curve model, but the equilibrium of the macro model does not depend on yields other than the short rate. Such a recursive structure between macro variables and yields is present also in studies focusing on the nominal bond premium puzzle, such as Hordahl, Tristani and Vestin (2008), Rudebusch and Swanson (2012), and Hollifield, Gallmeyer, Palomino and Zin (2017). In contrast to this literature, in our model macro variables and yields are interdependent.[9]

The second literature concerns housing finance in the monetary transmission mechanism. For the most part, this literature combines New-Keynesian features with the Iacoviello (2005)-type borrowing constraint, whereby the housing stock is used as a collateral against one-period loans.[10] A few studies consider long-term loans. Ghent (2012) and Wong (2016) focus on FRMs. While these authors specify FRMs in some detail, they model the loans as real, rather than nominal. In Ghent (2012), monetary policy has a small equilibrium effect on the long-term real rate, while in Wong (2016) the real rate is exogenous. Hedlund, Karahan, Mitman and Ozkan (2017) focus on ARMs. The analysis is carried out in a rich New-Keynesian heterogenous household model, containing also housing market search frictions and a government nominal debt. Aggregate

[9] On the other hand, relative to most of this literature, we compromise on the complexity of the yield curve model; in our case, it is based only on the expectations hypothesis, as in Gurkaynak et al. (2005) and Bekaert et al. (2010). We are also not concerned with all maturities, but only with the short and long rates. Generating sufficiently large term premia, and their time variation, within production economies has so far proved challenging, especially when capital is endogenous (Rudebusch and Swanson, 2008; van Binsbergen, Fernandez-Villaverde, Koijen and Rubio-Ramirez, 2012). Some progress is reported by Kung (2015).

[10] See Iacoviello (2010) for a brief overview of this literature. Attempts to incorporate FRMs into this framework include Rubio (2011), who models FRMs as one-period loans with an interest rate evolving in a sluggish manner, and Calza, Monacelli and Stracca (2013), who model FRMs as two-period loans.

housing stock is constant and there is no capital. Our model is more stylized, allowing for general equilibrium analysis of both mortgage types and a transparent characterization of the mechanisms, which may be useful for interpreting results of richer models in future research. Endogenous housing and capital also keep the model close to the DSGE models typically used for monetary policy analysis. Our previous work (Garriga et al., 2017) contains more details on housing and mortgages, but abstracts from endogenous labor, and thus short-run responses of output to nominal shocks, and New-Keynesian frictions.[11]

To proceed, Section 2 documents that the short rate contains a large common component with the long rate and interprets this finding on the basis of the macro-finance literature. Section 3 lays down the model. Section 4 describes its calibration. Section 5 reports the findings while Section 6 provides their analytical interpretation. Section 7 concludes and draws some tentative policy lessons.

# 2 Yield curve factors

The finance literature expresses yields as linear functions of a small number of factors (exogenous random variables). Typically, three latent factors are sufficient to account for over 99% of the movements in the yields across all maturities. Even two factors often go a long way. Here we employ the simplest such method, the principal component analysis, following closely Piazzesi (2006). More elaborate methods, such as estimated affine term structure models (), imply factors with similar statistical properties as those obtained by the principal component decomposition. We carry out the decomposition for a number of developed economies to show that the questions regarding interest rates studied in the model extend beyond the typical case of the United States. We then turn to the macro-finance literature for interpretation.

The PC analysis reveals that, like for the United States (e.g., Piazzesi, 2006), for a number of developed economies two factors are sufficient to describe all of

[11] As mortgages in our model are nominal, the paper is also related to studies on inflation shocks and real debt valuations. Among others, and in different settings, Doepke, Schneider and Selezneva (2015) focus on household total net debt positions, Hedlund (2016) on mortgage debt, Krause and Moyen (2016) on government debt, and Gomes, Jermann and Schmid (2016) on corporate debt.

the movements of nominal interest rates across maturities, including the short rate controlled by monetary policy.

Specifically, PC analysis decomposes fluctuations in $J$ yields into, at the most, $J$ orthogonal principal components. Let $\mathbf{Y}_t$ be a vector of $J$ nominal yields at time $t$ and $\text{var}(\mathbf{Y}_t) = \Omega\Lambda\Omega^\top$ be its variance-covariance matrix, where $\Lambda$ is a diagonal matrix of eigenvalues and $\Omega$ is a matrix of the associated eigenvectors. A $J \times 1$ vector of principal components is then given as $\mathbf{pc}_t = \Omega^{-1}(\mathbf{Y}_t - \mathbf{Y})$, where $\mathbf{Y}$ is the unconditional mean of the vector $\mathbf{Y}_t$. The variance of the $j$th principal component is equal to the $j$th element of the matrix $\Lambda$ and $\text{tr}(\Lambda) = \text{tr}(\text{var}(\mathbf{Y}_t))$; i.e., the sum of the variances of the principal components is equal to the sum of the variances of the individual yields.

We carry out the PC analysis for Australia, Canada, Germany, Japan, and the United States. These countries include both FRM and ARM countries. The sample is limited by our requirement of data availability for at least three maturities of government bonds for each country going back to at least mid 1970s. A selection of the yields for each country is plotted in the left-hand side columns of Figures 2 and 3.[12] Clearly, for all countries, the yields across maturities tend to move together. This is reflected in the first principal components plotted in the right-hand side columns of Figures 2 and 3. The second principal component, also plotted, accounts for the differences between the long and short yields.

Table 3 summarizes the statistical properties of the first principal component. As would be expected from the figures, the first principal component is much more volatile than the second principal component (measured by the ratio of their standard deviations) and accounts for a bulk of the volatility across maturities. Over 95%, and in most countries 98%, of the volatility is due to this factor; this percentage is for $\Lambda_1/\,\text{tr}(\Lambda)$. The second principal component essentially accounts for the remainder of the volatility; the other components have negligible effect. Furthermore, the first principal component is highly persistent (autocorrelation

[12] All data used in the PC analysis are from Haver: AUS (3M, 5YR, 10YR for 1972.Q1-2016.Q1); CAN (3M, 1-3YR, 3-5YR, 5-10YR, 10+YR for 1962.Q1-2015.Q1); GER (3M, 1YR, 2YR, 3YR, 4YR, 5YR, 6YR, 7YR, 8YR, 9YR, 10YR for 1972.Q4-2012.Q1); JAP (3M, 3YR, 5YR, 7YR, 9YR for 1975.Q4-2014.Q4); and US (3M, 1YR, 3YR, 5YR, 10YR, 20YR for 1953.Q2-2016.Q1). While the set of maturities and the sample period differ across countries, we chose to maximize the number of observations over sample consistency.

of around 0.98) and highly positively correlated with both short and long yields (0.93-0.98 and 0.97-0.99, respectively). Its correlation with inflation is also high (0.67-0.80).[13] All these properties are broadly in line with the properties of the level factor shock in the model.

# 3 The model

The economy's population is split into two groups, 'homeowners' and 'capital owners', with measures $\Psi$ and $(1-\Psi)$, respectively. Within each group, agents are identical. Homeowners own the economy's housing stock whereas capital owners own the economy's capital stock. Both agent types supply labor. This abstraction is motivated by cross-sectional observations by Campbell and Cocco (2003): The typical homeowner is a middle class household in the wealth distribution, with one major asset, a house, and almost no corporate equity. This is in contrast to households in the top quintile of the wealth distribution, who own the entire corporate equity in the economy and housing makes up a small fraction of their assets.[14]

Homeowners finance housing investment through mortgages with a given loan-to-value ratio. Mortgages are modeled as long-term loans specifying the *nominal* payments that homeowners have to make throughout the life of the loan (the model abstracts from default). By being long-term loans for house purchase, mortgages in the model resemble first mortgages, as opposed to home equity lines of credit, which are closer to the short-term loans in Iacoviello (2005). The model economy operates under either ARM contracts (like, e.g., Australia) or FRM contracts (like, e.g., Germany). Our focus is on modeling the key characteristics of these two basic mortgage contracts, rather than specific institutional details.[15]

[13]The data for inflation are for quarterly year-on-year changes in CPI. Source: FRED.

[14]The lowest two quintiles in the data are renters with little assets and little debt. These agents are not included in the model.

[15]Garriga, Kydland and Šustek (2016) consider a richer mortgage market structure, allowing for refinancing and mortgage choice between FRM and ARM contracts. But when they calibrate their model to the data, these additional features turn out not to affect the responses of the model economy to shocks in a substantial way. This is due to the fact that, even though the composition of *new loans* is sensitive to economic shocks, this translates to only small changes in the composition of the *outstanding stock* of debt, either in terms of ARM vs. FRM or

Capital owners are the mortgage investors in the model and price mortgages competitively by arbitrage. Financial markets are incomplete in the sense that the full set of state-contingent securities does not exist. The only other financial instrument available, apart from the mortgage, that the two agent types can trade is a noncontingent one-period bond. Due to the market incompleteness, the stochastic discount factors of the two agent types are not equalized state by state and risk sharing is limited.

The production side of the economy has standard New-Keynesian features. In fact, the model collapses into a standard representative agent New-Keynesian model with endogenous capital once homeowners (and thus also housing and mortgage markets) are removed. Monopolistic intermediate good producers combine capital and labor according to a common constant returns to scale (CRS) production function to produce goods that are used as inputs by perfectly competitive CRS final good producers. The intermediate good producers set prices in nominal terms, subject to price adjustment costs. Output of the final good can be used for consumption, investment in capital, and investment in housing, subject to a concave production possibilities frontier (PPF). The concavity of the PPF plays a similar role as investment adjustment costs used in New-Keynesian models. Monetary policy follows an interest rate feedback rule. Finally, taxes, transfers, and government expenditures are introduced into the model to ensure a sensible calibration, as explained in Section 4.

## 3.1 Capital owners

A representative capital owner (agent 1) maximizes expected life-time utility

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_{1t}, n_{1t}), \quad \beta \in (0,1),$$

refinanced loans. And it is the composition of the stock that predominantly matters for the behavior of the economy.

where $u(.,.)$ has the standard properties guaranteeing a unique interior solution, subject to a sequence of constraints

$$c_{1t}+q_{Kt}x_{Kt}+\frac{b_{1,t+1}}{p_t}+\frac{l_{1t}}{p_t}=[(1-\tau_K)r_t+\tau_K\delta_K]\,k_t+(1-\tau_N)\epsilon_w w_t n_{1t}+(1+i_{t-1})\frac{b_{1t}}{p_t}+\frac{m_{1t}}{p_t}+\tau_{1t}+\Pi_t, \tag{1}$$

$$k_{t+1}=(1-\delta_K)k_t+x_{Kt}.$$

Here, $c_{1t}$ is consumption, $n_{1t}$ is labor, $x_{Kt}$ is investment in capital, $q_{Kt}$ is a relative price, $b_{1,t+1}$ is holdings of the one-period nominal bond between periods $t$ and $t+1$, $p_t$ is the nominal price of the final good, $l_{1t}$ is nominal mortgage lending, $\tau_K$ is a capital income tax rate, $r_t$ is a real capital rental rate, $\delta_K$ is a capital depreciation rate, $k_t$ is capital, $\tau_N$ is a labor income tax rate, $\epsilon_w$ is the relative productivity of capital owners (a parameter), $w_t$ is the aggregate real wage rate, $i_{t-1}$ is the nominal interest rate on the one-period bond bought in the previous period, $m_{1t}$ is nominal payments from a pool of outstanding mortgages, $\tau_{1t}$ is government transfers, and $\Pi_t$ is profits of the intermediate good producers, assumed to be owned by the capital owner. The determination of mortgage payments is discussed in Section 2.3.

## 3.2 Homeowners

A representative homeowner (agent 2) maximizes expected life-time utility

$$E_0\sum_{t=0}^{\infty}\beta^t v(c_{2t},h_t,n_{2t}),$$

where $v(.,.,.)$ also has the standard properties, subject to a sequence of constraints

$$c_{2t}+q_{Ht}x_{Ht}+\frac{b_{2,t+1}}{p_t}=(1-\tau_N)w_t n_{2t}+(1+i_{t-1}+\Upsilon_{t-1})\frac{b_{2t}}{p_t}+\frac{l_{2t}}{p_t}-\frac{m_{2t}}{p_t}+\tau_{2t}, \tag{2}$$

$$\frac{l_{2t}}{p_t}=\theta q_{Ht}x_{Ht},$$

$$h_{t+1}=(1-\delta_H)h_t+x_{Ht}.$$

Here, $c_{2t}$ is consumption, $h_t$ is housing stock, $n_{2t}$ is labor, $x_{Ht}$ is housing investment, $q_{Ht}$ is its relative price, $b_{2,t+1}$ is holdings of the one-period nominal bond between periods $t$ and $t+1$, $l_{2t}$ is new nominal mortgage borrowing, $m_{2t}$ is nominal mortgage payments on outstanding debt, $\tau_{2t}$ is government transfers, $\theta$ is a loan-to-value ratio, and $\delta_H$ is a housing depreciation rate. Further, $\Upsilon_{t-1}$ is the homeowner's cost of participating in the bond market, taking the form of a spread over the market interest rate $i_{t-1}$. The cost is governed by a function $\Upsilon(-\widetilde{b}_{2t})$, where $\widetilde{b}_{2t} \equiv b_{2t}/p_{t-1}$. The function $\Upsilon(.)$ is assumed to be increasing and convex and satisfy the following additional properties: $\Upsilon(.) = 0$ when $\widetilde{b}_{2t} = 0$, $\Upsilon(.) > 0$ when $\widetilde{b}_{2t} < 0$ (the homeowner is borrowing), and $\Upsilon(.) < 0$ when $\widetilde{b}_{2t} > 0$ (the homeowner is saving). We think of $\Upsilon(.) > 0$ as capturing a premium for unsecured consumer credit, which is increasing in the amount borrowed. $\Upsilon(.) < 0$ can be interpreted as intermediation costs that reduce the homeowner's returns on savings below those of capital owners. The bond market cost function controls the extent to which the homeowner can use the bond market to smooth out fluctuations in income.[16]

## 3.3 Mortgages

Mortgages are modeled using the approximation of Kydland, Rupert and Šustek (forthcoming). Mortgage loans—like the agents—live forever, but their payment schedules resemble those of standard 30-year mortgages. Denoting by $d_{1t}$ the period-$t$ stock of outstanding nominal mortgage debt owed to the capital owner, the nominal mortgage payments received by the capital owner in period $t$ are

$$m_{1t} = (R_{1t} + \gamma_{1t})d_{1t}.$$

Here, $R_{1t}$ and $\gamma_{1t}$ are, respectively, the interest and amortization rates of the outstanding stock of debt. The variables comprising $m_{1t}$ are state variables evolving

[16] A technical role of the cost function is that, as in two-country business cycle models with incomplete asset markets, it prevents the one-period debt from becoming a random walk in a log-linear solution of the model. In other words, it keeps the log-linearized model stationary. In order to avoid the cost affecting the definition of aggregate output, it is rebated to the homeowner in a lump-sum way as a part of $\tau_{2t}$.

as

$$d_{1,t+1} = (1 - \gamma_{1t})d_{1t} + l_{1t}, \tag{3}$$

$$\gamma_{1,t+1} = (1 - \phi_{1t})(\gamma_{1t})^{\alpha} + \phi_{1t}\kappa, \tag{4}$$

$$R_{1,t+1} = \begin{cases} (1 - \phi_{1t})R_{1t} + \phi_{1t}i_t^F, & \text{if FRM,} \\ i_t, & \text{if ARM,} \end{cases} \tag{5}$$

where $i_t^F$ is the interest rate on new FRM loans and

$$\phi_{1t} \equiv \frac{l_{1t}}{d_{1,t+1}}$$

is the fraction of new loans in the outstanding mortgage debt next period. The amortization rate $\gamma_{1,t+1}$ and (in the FRM case) the interest rate $R_{1,t+1}$ thus evolve as weighted averages of the amortization and interest rates, respectively, of the existing stock and new loans. In equation (4), $\kappa, \alpha \in (0, 1)$ are parameters. Specifically, $\kappa$ is the initial amortization rate of a new loan and $\alpha$ controls the evolution of the amortization rate over time.[17]

In the FRM case, a first-order condition for $l_{1t}$ pins down an arbitrage-free $i_t^F$. Under such a mortgage interest rate, the capital owner is indifferent between extending new mortgage loans and rolling over the one-period bond from period $t$ on. Under ARM, the nominal interest rate of the one-period bond, $i_t$, is an arbitrage-free mortgage rate in the above sense. These properties are discussed further in Section 3. Under both contracts, as a result of the arbitrage free pricing, the capital owner is indifferent across investing in mortgages, bonds, and capital—in real terms, the present value of future cash flows from one unit of any of these assets is equal to one unit of current consumption. The capital owner's composition of period-$t$ investment (in terms of $x_{Kt}$, $b_{1,t+1}$, and $l_{1t}$) is pinned

[17] Even though each new loan has an infinite life, it shares under an appropriate choice of $\kappa$ and $\alpha$ the following features with standard mortgages. It gets essentially repayed within 30 years (120 periods, if the model is quarterly). The nominal mortgage payments are approximately constant for most of these 30 years (provided the loan's interest rate does not change). And at the start of the life of the loan most of the mortgage payments consist of interest payments, whereas towards the end of its life most of the payments consist of amortization payments. See Kydland et al. (forthcoming) for details. The adopted modeling of mortgages is convenient, as both the agents and the loans have an infinite life, thus allowing a simple recursive representation of the model with only a few state variables.

down by homeowners' demand for new mortgages and the one-period bond.

The evolution of mortgage payments that the homeowner has to make is governed by similar laws of motion as in the case of the capital owner:

$$m_{2t} = (R_{2t} + \gamma_{2t})d_{2t},$$

where

$$d_{2,t+1} = (1 - \gamma_{2t})d_{2t} + l_{2t}, \tag{6}$$

$$\gamma_{2,t+1} = (1 - \phi_{2t})\left(\gamma_{2t}\right)^{\alpha} + \phi_{2t}\kappa, \tag{7}$$

$$R_{2,t+1} = \begin{cases} (1 - \phi_{2t})R_{2t} + \phi_{2t}i_t^F, & \text{if FRM,} \\ i_t, & \text{if ARM,} \end{cases} \tag{8}$$

with $\phi_{2t} \equiv l_{2t}/d_{2,t+1}$. Demand for new mortgages is determined by the homeowner's choice of $x_{Ht}$ and the financing constraint $l_{2t} = \theta p_t q_{Ht} x_{Ht}$.

### 3.4 Production

Perfectly competitive final good producers, of which there is a measure one, produce a single good $Y_t$ using as inputs a continuum of goods $y_t(j)$, $j \in [0, 1]$. The representative producer solves a static profit maximization problem

$$\max_{Y_t, \{y_t(j)\}_0^1} p_t Y_t - \int_0^1 p_t(j) y_t(j) dj \quad \text{subject to} \quad Y_t = \left[\int_0^1 y_t(j)^{\varepsilon} dj\right]^{1/\varepsilon},$$

where $p_t(j)$ is the nominal price of an intermediate good $j$ and $\varepsilon \in (0, 1]$. As all final good producers are the same, and there is a measure one of them, $Y_t$ is also aggregate output. A first-order condition of this problem gives a demand function for good $j$

$$y_t(j) = \left[\frac{p_t}{p_t(j)}\right]^{\frac{1}{1-\varepsilon}} Y_t. \tag{9}$$

The producer of the intermediate good $j$ is a monopolist in market $j$. It faces the Calvo-style price stickiness and, if allowed to change its price in period $t$, solves the dynamic maximization problem

$$\max_{p_t(j)} E_t \sum_{\iota=0}^{\infty} \psi^{\iota} Q_{1,t+\iota} \left[ \frac{p_t(j)}{p_{t+\iota}} y_{t+\iota}(j) - \chi_{t+\iota} y_{t+\iota}(j) \right], \quad j \in [0,1], \tag{10}$$

where $Q_{1,t+\iota} \equiv \beta u_{c,t+\iota}/u_{ct}$ is the stochastic discount factor of the capital owner, $\chi_{t+\iota}$ is a real marginal cost, and $y_{t+\iota}(j)$ is given by the demand function (9), with $p_{t+\iota}(j) = p_t(j)\ \forall \iota$.[18] The expression in the square brackets is the per-period profit and $\psi \in [0,1]$ is the probability that the producer will not be able to change its price in a given period. By the law of large numbers, it is equal to the fraction of producers not changing prices.

The real marginal cost $\chi_t$ is given by a linear cost function of a static cost minimization problem

$$\chi_t y_t(j) = \min_{k_t(j), n_t(j)} r_t k_t(j) + w_t n_t(j) \quad \text{subject to} \quad A k_t(j)^{\varsigma} n_t(j)^{1-\varsigma} - \Delta = y_t(j).$$

Here, $A$ is a constant technology level and $k_t(j)$ and $n_t(j)$ are capital and labor, respectively, used by producer $j$.[19] Further, $\Delta$ is a fixed cost, which is a common feature of New-Keynesian models with capital, ensuring that profits in steady state are equal to zero. This is relevant for mapping the parameter $\varsigma$ to National Income and Product Accounts. The first-order condition of the cost minimization problem is

$$\frac{w_t}{r_t} = \left( \frac{1-\varsigma}{\varsigma} \right) \frac{k_t(j)}{n_t(j)}, \tag{11}$$

which sets relative factor prices equal to the marginal rate of technological substitution. The cost function then yields $\chi_t \equiv A^{-1}(r_t/\varsigma)^{\varsigma}[w_t/(1-\varsigma)]^{1-\varsigma}$. When this expression for the marginal cost is combined with the above first-order condition

[18] Notation such as $u_{ct}$ means the first derivative of the function $u$ with respect to argument $c$, evaluated in period $t$.

[19] In this paper we focus only on the real effects of nominal shocks, so TFP shocks or any other real shocks are abstracted from. $A$ is therefore just a parameter. In Garriga et al. (2016) we subject the model (a version without the New-Keynesian features) to multiple shocks, including TFP shocks, and compare the model's business cycle properties with the data, as a form of model cross-validation.

(11), we get

$$\chi_t = \frac{1}{A(1-\varsigma)}\left[\frac{n_t(j)}{k_t(j)}\right]^{\varsigma} w_t = \frac{1}{A(1-\varsigma)}\left[\frac{\overline{y}_t(j)}{Ak_t(j)}\right]^{\frac{\varsigma}{1-\varsigma}} w_t, \tag{12}$$

where $\overline{y}_t(j) \equiv y_t(j) + \Delta$. The second equality follows by substituting in for $n_t(j)$ from the production function. This expression will be relevant in Section 3.

The aggregate PPF is assumed to be nonlinear. Specifically,

$$C_t + q_{Kt}X_{Kt} + q_{Ht}X_{Ht} + G = Y_t, \tag{13}$$

where $C_t \equiv (1-\Psi)c_{1t} + \Psi c_{2t}$, $X_{Kt} \equiv (1-\Psi)x_{Kt}$, $X_{Ht} \equiv \Psi x_{Ht}$, and $G$ is (constant) government expenditures. Further, $q_{Kt}$ is the marginal rate of transformation between consumption and capital investment and $q_{Ht}$ is the marginal rate of transformation between consumption and housing investment (in steady state, the rates of transformation are normalized to be equal to one). Under perfect competition, the rates of transformation are equal to relative prices of capital and housing investment in terms of consumption, as has already been assumed in the budget constraints. The rates of transformation are given by strictly increasing convex functions $q(X_{Kt})$ and $q(X_H)$, which make the economy's PPF concave. This specification is akin to that of Fisher (1997) and Huffman and Wynne (1999) and is meant to capture, in a reduced-form way, the costs of moving factors of production across different sectors (e.g., between construction and nondurable goods). As noted above, the concavity of the PPF works in a similar way as investment adjustment costs, which are a standard feature of New-Keynesian models with capital (the reason why will become apparent below).

## 3.5 Monetary policy

Monetary policy is modeled as an interest rate feedback rule with two shocks, $\mu_t$ and $\eta_t$,

$$i_t = i + \mu_t - \pi + \nu_\pi(\pi_t - \mu_t) + \eta_t, \quad \nu_\pi > 1. \tag{14}$$

Here, $i$ and $\pi$ are the steady-state short-term nominal interest and inflation rates, respectively, $\pi_t \equiv p_t/p_{t-1} - 1$ is the inflation rate between periods $t$ and $t-1$, and $\nu_\pi$ is a weight on deviations of the inflation rate from a stochastic inflation target $\mu_t$. The inflation target has an unconditional mean equal to $\pi$ and follows a stationary AR(1) process $\mu_{t+1} = (1-\rho_\mu)\pi + \rho_\mu \mu_t + \xi_{\mu,t+1}$, where $\xi_{\mu,t+1}$ is a mean-zero innovation with standard deviation $\sigma_\mu$. The other shock has an unconditional mean equal to zero and follows a stationary AR(1) process $\eta_{t+1} = \rho_\eta \eta_t + \xi_{\eta,t+1}$, where $\xi_{\eta,t+1}$ is a mean-zero innovation with standard deviation $\sigma_\eta$. Both shocks are observed by the agents.[20]

Inflation target shocks have been considered by, e.g., Smets and Wouters (2003), Ireland (2007), Atkeson and Kehoe (2009), and Krause and Moyen (2016).[21] Assuming the inflation target shock is highly persistent, it plays a role of a 'level factor shock', shifting short- and long-term nominal interest rates approximately equally, as discussed below. The second shock is a 'standard monetary policy shock' studied in the New-Keynesian literature (e.g., Galí, 2015, among many others). In order to generate the typical New-Keynesian responses, the persistence of this shock has to be fairly low. It thus essentially only affects the short rate and thus the long-short spread. Together, the two shocks allow the model to be consistent with both, the New-Keynesian responses identified in VARs and the empirical persistence of the FRM rate.[22]

## 3.6 Equilibrium

In equilibrium, the following conditions are satisfied: (i) the capital owner and the homeowner solve their respective maximization problems, choosing contingency plans for $c_{1t}$, $n_{1t}$, $x_{Kt}$, $k_{t+1}$, $b_{1,t+1}$, and $l_{1t}$ (capital owner) and for $c_{2t}$, $n_{2t}$, $x_{Ht}$, $h_{t+1}$, $b_{2,t+1}$, and $l_{2t}$ (homeowner); (ii) intermediate good producers solve their respective optimization problems, choosing $k_t(j)$ and $n_t(j)$ and, if allowed, $p_t(j)$; (iii) the relative prices $q_{Kt}$ and $q_{Ht}$ are given by the respective marginal rates of transformation; (iv) monetary policy follows the interest rate rule; and (v)

[20] The specification of the policy rule abstracts from responding to fluctuations in output and from interest rate smoothing (a weight on past nominal interest rates). We have experimented with these features but found them to have only a limited effect on the results. In the interest of a more transparent exposition, these features have therefore been dropped from the model.

[21] See Ireland (2007) for further discussion.

[22] Through out the paper, we use the terms 'persistent shock' and 'level factor shock' and the terms 'temporary shock' and 'standard monetary policy shock' interchangeably.

mortgage, bond, labor, capital, and goods markets clear:

$$(1-\Psi)l_{1t} = \Psi l_{2t},$$

$$(1-\Psi)b_{1,t+1} + \Psi b_{2,t+1} = 0,$$

$$\int_0^1 n_t(j) = \epsilon_w N_{1t} + N_{2t} \equiv N_t,$$

$$\int_0^1 k_t(j) = K_t,$$

$$C_t + q_{Kt}X_{Kt} + q_{Ht}X_{Ht} + G = Y_t.$$

In the above, $N_{1t} \equiv (1-\Psi)n_{1t}$, $N_{2t} \equiv \Psi n_{2t}$, and $K_t \equiv (1-\Psi)k_t$. As capital owners' and homeowners' labor inputs are perfect substitutes, capital owners' wage rate is $\epsilon_w w_t$, whereas homeowners' wage rate is $w_t$, as has already been assumed in the respective budget constraints. Aggregate consistency further implies: $(1-\Psi)d_{1t} = \Psi d_{2t}$, $\gamma_{1t} = \gamma_{2t}$, and $R_{1t} = R_{2t}$. As a consequence, $(1-\Psi)m_{1t} = \Psi m_{2t}$.[23] For the quantitative experiments, the equilibrium is computed using standard log-linearization methods.

# 4 The channels of real effects

Nominal rigidities in the model come from two sources: sticky prices and mortgage contracts. In this section we discuss the equilibrium consequences of each rigidity in isolation in order to facilitate the interpretation of the quantitative findings later on. First, however, it is instructive to partially characterize the equilibrium mappings from the two shocks into the nominal interest rate and inflation.

[23]The government budget constraint is given by $G + (1-\Psi)\tau_{1t} + \Psi\overline{\tau}_2 = \tau_K(r_t - \delta_K)K_t + \tau_N w_t(\epsilon_w N_{1t} + N_{2t})$. It holds by Walras' law. Here, $\overline{\tau}_2$ is a parameter and $\tau_{1t}$ takes up the slack to ensure that the budget constraint is satisfied state-by-state. Transfers to the homeowner are given by $\tau_{2t} = \overline{\tau}_2 - (b_{2t}/p_t)\Upsilon_{t-1}$; i.e., the participation cost is rebated back to the homeowner in a lump-sum way in order not to affect aggregate output. In steady state, the participation cost is equal to zero.

## 4.1 Nominal shocks, nominal interest rate, and inflation

Without the loss of generality, in the following discussion it is useful to abstract from the capital income tax rate to simplify notation. The capital owner's first-order conditions for $b_{1,t+1}$ and $x_{Kt}$ yield

$$1 = E_t\left(Q_{1,t+1}\frac{1+i_t}{1+\pi_{t+1}}\right) \quad \text{and} \quad 1 = E_t\left[Q_{1,t+1}\left(\frac{r_{t+1}}{q_{Kt}} + \frac{q_{K,t+1}(1-\delta_K)}{q_{Kt}}\right)\right]. \tag{15}$$

In the second equation, the first term in the inner brackets can be interpreted as a dividend yield, while the second term as a capital gain. Once log-linearized around a steady state, the two equations yield the Fisher equation

$$i_t - E_t\pi_{t+1} \approx E_t\left[r_{t+1} + (1-\delta_K)q_{K,t+1} - q_{Kt}\right] \equiv r_t^*, \tag{16}$$

where $r_t^*$ is the ex-ante real interest rate and (abusing notation) all variables are in percentage point deviations from steady state. Combining equation (16) with the policy rule (14), assuming $\rho_\mu$ close to one and excluding explosive paths for inflation, yields

$$i_t \approx \sum_{\iota=0}^{\infty}\left(\frac{1}{\nu_\pi}\right)^{\iota} E_t r_{t+\iota}^* - \frac{\rho_\eta}{\nu_\pi - \rho_\eta}\eta_t + \mu_t. \tag{17}$$

Observe that unless the effect of $\mu_t$ is sufficiently offset by an endogenous response of the future path of the real rate, the $\mu_t$ shock generates almost permanent one-for-one changes in $i_t$. It thus affects not only the short rate but also the long rate ($i_t^F$) and, in this sense, works like a level factor shock. Substituting equation (17) into the policy rule (14) provides an analogous expression for the inflation rate

$$\pi_t \approx \frac{1}{\nu_\pi}\sum_{\iota=0}^{\infty}\left(\frac{1}{\nu_\pi}\right)^{\iota} E_t r_{t+\iota}^* - \frac{1}{\nu_\pi - \rho_\eta}\eta_t + \mu_t, \tag{18}$$

where the effect of $\mu_t$ is the same as on the nominal interest rate.

From equations (17) and (18) follows that the effect of the standard monetary policy shock $\eta_t$ on both the short-term nominal interest rate and inflation is, ceteris paribus, negative. In order to generate the typical New-Keynesian response of the two variables to a positive $\eta_t$ shock—i.e., a decline in $\pi_t$ but an increase in

$i_t$—the ex-ante real rate has to increase: observe that the real rate has a larger positive effect on the nominal interest rate than on inflation, whereas $\eta_t$ has a larger direct negative effect on inflation than on the nominal interest rate. Observe further that the negative effect of the shock increases with its persistence. Thus, in order to produce an increase in the nominal interest rate alongside a decline in inflation, the persistence of the shock cannot be too high. Otherwise, the direct negative effect of the shock on the nominal interest rate may outweight any positive effect coming from an increase in the real rate.

## 4.2 Sticky price channel

As noted above, if homeowners are removed ($\Psi = 0$), the model collapses into a standard representative agent New-Keynesian model with endogenous capital. If homeowners are present but mortgages are removed ($\theta = 0$), the model becomes a two-agent New-Keynesian model with endogenous capital and housing, in which housing investment is equity financed. All aspects of the model related to price stickiness are contained in the optimization problem (10). As demonstrated in numerous texts (e.g., Galí, 2015), the log-linearized version of the first-order condition for this problem, once aggregation is imposed, yields the New-Keynesian Phillips curve (NKPC)

$$\pi_t = \frac{(1-\psi)(1-\beta\psi)}{\psi}\Theta\widehat{\chi}_t + \beta E_t \pi_{t+1}, \tag{19}$$

where $\Theta \equiv (1-\varsigma)/[1-\varsigma+\varsigma/(1-\varepsilon)] \geq 0$ and $\widehat{\chi}_t$ is the percentage deviation of the marginal cost from steady state.[24] This equilibrium condition embodies the nominal rigidity in the model due to sticky prices. For $\beta$ close to one, it provides a negative relationship between an expected change in the inflation rate, $E_t\pi_{t+1} - \pi_t$, and the real marginal cost, $\widehat{\chi}_t$. For a highly persistent inflation rate, $E_t\pi_{t+1} - \pi_t$ is close to zero, implying $\widehat{\chi}_t \approx 0$. In this case, monetary policy has

[24]Equation (19) is derived under the common assumption that the steady-state inflation rate is equal to zero. This assumption provides a more elegant expression for the linearized NKPC than would otherwise be the case. For expositional purposes, this section therefore proceeds under this common assumption, even though the model is computed under a calibrated non-zero steady-state inflation rate.

almost no real effects. If, in contrast, the inflation rate is not very persistent, then $E_t\pi_{t+1} - \pi_t \neq 0$ and $\widehat{\chi}_t \neq 0$. In this case, monetary policy has real effects.

Appendix A.1 establishes that percentage deviations of the marginal cost are positively related to percentage deviations of aggregate output, $\widehat{Y}_t$.[25] Equation (19) thus provides a negative relationship between $E_t\pi_{t+1} - \pi_t$ and $\widehat{Y}_t$. As a result, a shock that *temporarily* reduces inflation, thus generating $E_t\pi_{t+1} - \pi_t > 0$, produces a decline in output, $\widehat{Y}_t < 0$. In the face of the output drop, consumption smoothing by capital owners requires a drop in capital investment, which leads to a decline in $q_{Kt}$ and thus positive expected capital gains, $E_t(1-\delta_K)q_{K,t+1} - q_t > 0$.[26] A sufficiently large increase in capital gains then leads to an increase in the ex-ante real interest rate $r_t^*$, as follows from equation (16). The greater is the curvature of the PPF, the less can consumption be smoothed out in equilibrium. Therefore, the greater is the increase in expected capital gains, and thus in the ex-ante real interest rate. This mechanism generates the typical New-Keynesian response to a temporary monetary policy shock; i.e., the ex-ante real rate increases while output and inflation fall, with a sufficiently large increase in the real rate producing also an increase in the nominal rate, as discussed above. As this is an aggregate effect (i.e., aggregate output falls), the decline in output is born by both agent types, albeit to a possibly different extent.[27]

## 4.3 Mortgage channel

To highlight the role of mortgages, nominal prices in this section are assumed to be fully flexible (i.e., $\psi = 0$). The NKPC (19) then implies $\widehat{\chi}_t = 0$ (i.e., $\chi_t = \chi$). That is, the marginal cost is constant, equal to its steady-state value, which is given by a standard static profit maximization condition of a monopolist, $(1/\varepsilon)\chi = p(j)/p$; i.e., the relative price of good $j$ is set as a constant markup over

[25] A positive relationship between $\widehat{\chi}_t$ and $\widehat{Y}_t$ is easier to derive in the textbook New-Keynesian model without capital, in which $\widehat{C}_t = \widehat{Y}_t$.

[26] A drop in capital investment can occur through a direct channel, by capital owners reducing capital investment for given holdings of bonds, and through an indirect channel, by homeowners reducing holdings of the bonds, whose proceeds could otherwise be used to support capital investment by capital owners.

[27] Again, these responses are easier to establish in the textbook New-Keynesian model without capital.

marginal costs. When $\varepsilon = 1$, this condition yields $\chi = 1$. The marginal cost is equal to the relative price of good $j$, which is equal to one, as all goods are perfectly substitutable; a standard profit maximization condition under perfect competition. As there are no monopoly profits, we set $\Delta = 0$. Equation (12), with $\chi_t = 1$, then yields $w_t = (1-\varsigma)AK_t^{\varsigma}N_t^{-\varsigma}$. Combining this expression with the cost minimization condition (11) gives $r_t = \varsigma AK_t^{\varsigma-1}N_t^{1-\varsigma}$. Thus, under perfect competition, the wage rate and the rental rate are equalized with the respective marginal products of labor and capital.

Mortgages introduce a nominal rigidity into the model due to the multi-period term over which homeowners make nominal payments. The nominal rigidity shows up in two places: as an income effect in the budget constraints of the two agents and as a price effect in a first-order condition of the homeowner for housing. The income effect occurs due to the effects of inflation surprises on the real value of payments on *outstanding* mortgage debt, while the price effect concerns the effects of expected future inflation on the cost of *new* mortgage borrowing.[28]

### 4.3.1 Income effect

It is convenient for this and the next section to write the real mortgage payments in the budget constraints (1) and (2) as

$$\frac{m_{et}}{p_t} \equiv \widetilde{m}_{et} = \frac{R_{et} + \gamma_{et}}{1 + \pi_t}\widetilde{d}_{et} \tag{20}$$

where $\widetilde{d}_{et} \equiv d_{et}/p_{t-1}$ and $e \in \{1, 2\}$. Recall that in period $t$, the variables $R_{et}$, $\gamma_{et}$, and $d_{et}$ that make up the nominal payments are pre-determined and from period $t$ on evolve according to the laws of motion (3)-(5), for $e = 1$, and (6)-(8), for $e = 2$. To focus on outstanding debt, let us set $l_{e,t+\iota} = 0$, for $\iota = 0, 1, 2, \ldots$

It is clear from equation (20) that, as the numerator is predetermined in period $t$, an unexpected increase in $\pi_t$ has a standard income effect under both FRM and ARM. It reduces the real value of mortgage payments in period $t$ and thus redistributes income from capital owners to homeowners.

[28]Bernanke and Gertler (1995) and Mishkin (2007) refer to the income effect also as a 'cash flow' or 'household balance sheet' effect.

Suppose, however, that the increase in the inflation rate is persistent and assume there are no further inflation surprises. From period $t+1$ on, the effects of higher inflation are different under FRM and ARM. Under FRM, the sequence of real mortgage payments is

$$\widetilde{m}_{e,t+1} = \frac{R_{et} + \gamma_{e,t+1}}{(1+\pi_{t+1})(1+\pi_t)}(1-\gamma_{et})\widetilde{d}_{et},$$

$$\widetilde{m}_{e,t+2} = \frac{R_{et} + \gamma_{e,t+2}}{(1+\pi_{t+2})(1+\pi_{t+1})(1+\pi_t)}(1-\gamma_{e,t+1})(1-\gamma_{et})\widetilde{d}_{et}, \quad \text{etc.},$$

where $R_{et}$ is constant and $\gamma_{e,t+\iota}$ converges to one over time.[29] Higher inflation thus reduces the real value of mortgage payments under FRM and, through accumulated inflation, the size of this effect increases over time.

Under ARM, the sequence of real mortgage payments is

$$\widetilde{m}_{e,t+1} = \frac{i_t + \gamma_{e,t+1}}{(1+\pi_{t+1})(1+\pi_t)}(1-\gamma_{et})\widetilde{d}_{et}, \tag{21}$$

$$\widetilde{m}_{e,t+2} = \frac{i_{t+1} + \gamma_{e,t+2}}{(1+\pi_{t+2})(1+\pi_{t+1})(1+\pi_t)}(1-\gamma_{e,t+1})(1-\gamma_{et})\widetilde{d}_{et}, \quad \text{etc.},$$

The difference, compared with FRM, is that the mortgage rate of the outstanding debt is equal to the short-term nominal interest rate, which can change over time. To demonstrate the consequence of this aspect of ARM loans, let us first focus on $\widetilde{m}_{e,t+1}$. Holding the ex-ante real rate constant, a higher $\pi_{t+1}$ translates through the Fisher equation (16) into equiproportionally higher $i_t$. As a result, and in contrast to the FRM case, $\widetilde{m}_{e,t+1}$ increases. To see this, focus on the ratio in equation (21), which can be written as

$$\frac{i_t + \gamma_{e,t+1}}{(1+\pi_{t+1})(1+\pi_t)} \approx \frac{i_t + \gamma_{e,t+1}}{1+\pi_{t+1}+\pi_t} \approx i_t + \gamma_{e,t+1} \approx r^* + \pi_{t+1} + \gamma_{e,t+1},$$

where the first two approximations hold for sufficiently small inflation rates and $\gamma_{e,t+1}$ sufficiently smaller than one. Thus, in contrast to FRM, a higher $\pi_{t+1}$ leads to a higher $\widetilde{m}_{e,t+1}$. This front-end property reflects the fact that at the early

[29] $\gamma_{e,t+\iota}$ converges to one because $\gamma_{et} \in (0,1)$ and $\alpha \in (0,1)$; see the law of motion (4) or (7) for $l_{e,t+\iota} = 0$, $\iota = 0, 1, 2, \ldots$.

stages in the life of a mortgage, a bulk of the payments are interest payments. Over time, however, the effects of accumulated inflation get stronger. To see this back-end property of the loan, notice that for a sufficiently high $\iota$, the ratio can be written as

$$\frac{i_{t+\iota} + \gamma_{e,t+\iota}}{1 + \pi_{t+\iota} + \dots \pi_{t+1} + \pi_t} \approx \frac{r^* + \pi_{t+\iota} + \gamma_{e,t+\iota}}{1 + \pi_{t+\iota} + \dots \pi_{t+1} + \pi_t} \approx \frac{\gamma_{e,t+\iota}}{1 + \pi_{t+\iota} + \dots \pi_{t+1} + \pi_t},$$

where the last approximation is due to $\gamma_{t+\iota} \to 1$ and $r^*$ and $\pi_{t+\iota}$ being assumed to be relatively small. Observe that for $\gamma = 1$ (i.e., a one-period loan, a short cut often taken in the literature to model ARM), neither the front-end nor the back-end property of ARM is present and the only effect of inflation is the standard income effect on $\widetilde{m}_{et}$ in equation (20).

To sum up the income effect: After the initial period $t$, higher inflation reduces real mortgage payments under FRM, but increases real mortgage payments under ARM, at least in the short run. While the reduction under FRM is gradual, the increase under ARM is immediate. Over time, however, as the loan gets amortized and interest payments become a small fraction of mortgage payments, the income effect under ARM starts to resemble the income effect under FRM.

#### 4.3.2 Price effect

The price effect concerns the cost of new mortgage borrowing and thus the effective price of housing investment. The first-order condition for $x_{Ht}$ takes the form

$$v_{ct} q_{Ht} (1 + \tau_{Ht}) = \beta E_t V_{h,t+1}, \tag{22}$$

where $V_{h,t+1}$ is the derivative of the homeowner's value function with respect to $h_{t+1}$ in a recursive formulation of the problem and $\tau_{Ht}$ is a wedge, discussed below, summarizing the effect of mortgage finance on the optimal choice of $x_{Ht}$. Notice that the wedge affects the first-order condition in a similar way as the relative price of new housing $q_{Ht}$, hence the term 'price effect'. To see how nominal interest rates and inflation affect the real cost of a new mortgage loan in isolation, it is instructive to consider a once-and-for-all housing investment decision in period $t$, without any outstanding debt. That is, assume $d_{2t} = 0$, $x_{Ht} > 0$, and $x_{H,t+\iota} = 0$

for $\iota = 1, 2, \ldots$. In this case, the wedge is[30]

$$\tau_{Ht} \equiv \theta \left\{ -1 + E_t \left[ Q_{2,t+1} \frac{i^M_{t+1} + \gamma_{2,t+1}}{1+\pi_{t+1}} + Q_{2,t+2} \frac{(i^M_{t+2} + \gamma_{2,t+2})(1-\gamma_{2,t+1})}{(1+\pi_{t+1})(1+\pi_{t+2})} + ... \right] \right\}. \tag{23}$$

Here, $Q_{2,t+\iota} \equiv \beta v_{c,t+\iota}/v_{ct}$ is the stochastic discount factor of the homeowner and $i^M_{t+\iota} = i^F_t$ under FRM and $i^M_{t+\iota} = i_{t+\iota-1}$ under ARM. Observe that the term inside the square brackets is a present value of real mortgage payments from the homeowner's perspective (i.e., the payments are discounted with the homeowner's stochastic discount factor).

The FRM interest rate is determined by a first-order condition of the capital owner with respect to $l_{1t}$, which takes the form

$$1 = E_t \left[ Q_{1,t+1} \frac{i^F_t + \gamma_{1,t+1}}{1+\pi_{t+1}} + Q_{1,t+2} \frac{(i^F_t + \gamma_{1,t+2})(1-\gamma_{1,t+1})}{(1+\pi_{t+1})(1+\pi_{t+2})} + ... \right], \tag{24}$$

where $Q_{1,t+\iota} \equiv \beta u_{c,t+\iota}/u_{ct}$. It is straightforward to also verify that the following holds in the case of ARM

$$1 = E_t \left[ Q_{1,t+1} \frac{i_t + \gamma_{1,t+1}}{1+\pi_{t+1}} + Q_{1,t+2} \frac{(i_{t+1} + \gamma_{1,t+2})(1-\gamma_{1,t+1})}{(1+\pi_{t+1})(1+\pi_{t+2})} + ... \right]. \tag{25}$$

These two conditions state that, from the capital owner's perspective, the present value of real mortgage payments on a one dollar loan has to be equal to one dollar. These two conditions are the mortgage counterparts to the no-arbitrage conditions for bonds and capital (15).

Observe that if asset markets were complete ($Q_{1,t+\iota} = Q_{2,t+\iota}$) then the present value in equation (23) would be equal to one and the wedge would be equal to zero. Under incomplete markets, $Q_{1,t+\iota} \neq Q_{2,t+\iota}$ and the wedge in general is not equal to zero and depends on nominal variables. To see how the price effect works, assume again that the real rate $r^*$ is constant and that there is no uncertainty about future inflation (the case of perfect foresight is the easiest case in which to explain, without the loss of generality, the price effect).

It is convenient to start with the ARM case. Suppose $\pi_{t+1}$ increases. Through the Fisher effect, this leads to an equiproportional increase in $i_t$. As a result, the

[30] See Appendix for derivation.

real mortgage payment in period $t+1$ increases, since as in the case of the income effect, the dominant effect is the interest rate effect. The same argument applies for other periods $t+\iota$ if the inflation rate increases persistently. However, as in the case of the income effect, there is again an $\iota$ such that the effect of accumulated inflation starts to dominate the effect of higher nominal interest rates. But if this occurs in a sufficiently distant future, so that those future payments are sufficiently discounted, the wedge increases, making housing investment more expensive.

In the FRM case, the pricing equation (24) shows that, for a given sequence of $Q_{1,t+\iota}$, the mortgage rate $i_t^F$ depends positively on future inflation. Higher expected future inflation thus increases $i_t^F$. Similar arguments as in the ARM case therefore apply, at least qualitatively, and higher inflation makes new FRM loans more expensive to the homeowner. Thus, in contrast to the income effect, the price effect works qualitatively in the same direction under FRM and ARM.

### 4.3.3 Summary of the mortgage channel

To summarize the mortgage channel, it operates by affecting the relative price of new housing and the distribution of current and expected future disposable income. Unlike the sticky price channel, it does not directly affect producers. Under ARM, both the price and income effects hurt homeowners when inflation increases. Under FRM, the price effect hurts homeowners while the income effect benefits them. In contrast to the sticky price channel, the size of the price and income effects increases with inflation persistence.

## 5 Calibration

The calibration is based on U.S. targets, details of which can be found in Garriga et al. (2016). The New-Keynesian parameters are the standard ones in the literature. The mechanism under investigation, however, is not specific to the U.S. economy and applies more generally. The U.S. calibration simply provides an example of a reasonable parameterization of the model. Most of the targets are based on data for the post-war period, until 2007, and come from National Income and Product

Accounts (NIPA) and the Survey of Consumer Finances (SCF). One period in the model corresponds to one quarter.

## 5.1 Functional forms

The capital owner's per-period utility function is $u(c_1, n_1) = \log c_1 - [\omega_1/(1+\sigma_1)]n_1^{(1+\sigma_1)}$, where $\omega_1 > 0$ and $\sigma_1 > -1$. Such specification is common in the New-Keynesian literature. The homeowner's utility function is analogous, except that it also depends on housing: $u(c_2, h, n_2) = \varrho \log c_2 + (1-\varrho)\log h - [\omega_2/(1+\sigma_2)]n_2^{(1+\sigma_2)}$, with $\omega_2 > 0$, $\sigma_2 > -1$, and $\varrho \in (0,1)$. The production function $AK^{\varsigma}N^{1-\varsigma}$ is also standard. The function governing the curvature of the production possibilities frontier is $q_H(X_{Ht}) = \exp(\zeta_H(X_{Ht} - X_H))$, where $\zeta_H > 0$ and $X_H$ is the steady-state ratio of housing investment to output (output is normalized to be equal to one in steady state). Analogously, $q_K(X_{Kt}) = \exp(\zeta_K(X_{Kt} - X_K))$, where $\zeta_K > 0$ and $X_K$ is the steady-state ratio of capital investment to output. Finally, $\Upsilon(-\widetilde{B_t}) = \exp(-\vartheta\widetilde{B}_t) - 1$, where $\vartheta > 0$ and in steady-state $\widetilde{B} = 0$. All the functional forms satisfy the properties assumed in the description of the model.

## 5.2 Parameter values

The parameter values are listed in Table 1, where they are organized into nine categories: $\Psi$ (population); $\beta$, $\sigma_1$, $\sigma_2$, $\omega_1$, $\omega_2$, $\varrho$ (preferences); $\varsigma$, $\Delta$, $\delta_K$, $\delta_H$, $\epsilon_w$, $\zeta_K$, $\zeta_H$ (technology); $G$, $\tau_N$, $\tau_K$, $\overline{\tau}_2$ (fiscal); $\varepsilon$, $\psi$ (goods market); $\theta$, $\kappa$, $\alpha$ (mortgage market); $\vartheta$ (bond market); $\overline{\pi}$, $\nu_\pi$ (monetary policy); and $\rho_\mu$, $\rho_\eta$, $\sigma_\mu$, $\sigma_\eta$ (stochastic processes). Most parameters can be assigned values independently, without solving a system of steady-state equations. Six parameters ($\omega_1$, $\omega_2$, $\varrho$, $\epsilon_w$, $\tau_K$, $\overline{\tau}_2$) have to be obtained jointly from such steady-state relations. And another six parameters ($\zeta_K$, $\zeta_H$, $\rho_\mu$, $\rho_\eta$, $\sigma_\mu$, $\sigma_\eta$) are assigned values on the basis of the dynamic properties of the model; these last six parameters do not affect the steady state and thus the values of the other parameters.

### 5.2.1 Parameters calibrated independently

We start with a description of the parameters in the first group. The population parameter $\Psi$ is set equal to 2/3. This corresponds to the notion that the typical homeowner comes from the middle class, the 3rd and 4th quintiles of the wealth distribution, whereas the typical owner of capital comes from the 5th quintile (Campbell and Cocco, 2003). The parameter controlling the elasticity of labor supply is treated symmetrically across homeowners and capital owners. Guided by the New-Keynesian literature, $\sigma_1 = \sigma_2 = 1$. Regarding $\beta$, the Euler equation for $l_{1t}$ constrains $i^F$ to equal to $i$ in steady state. The Euler equation for $b_{1,t+1}$ then relates $i$ and $\pi$ to $\beta$. Using $i^F = 0.0233$ and $\pi = 0.0113$, implies $\beta = 0.9883$. The parameter $\varsigma$ corresponds to the NIPA share of capital income in output and is set equal to 0.283. As in the New-Keynesian literature, the fixed cost is set so as to ensure zero steady-state profits. This requires $\Delta = 0.2048$. The depreciation rates $\delta_K$ and $\delta_H$ are set equal to 0.02225 and 0.01021, respectively, to be consistent with the average flow-stock ratios for capital and housing, $X_K/K$ and $X_H/H$. Based on NIPA, the appropriate counterpart to $G$ makes up on average 0.138 of output and the aggregate labor income tax rate $\tau_N$ is 0.235. The parameter $\varepsilon$ governing the goods elasticity of substitution and the Calvo parameter $\psi$ (the fraction of firms not adjusting prices) are set equal to 0.83 and 0.7, respectively—standard values in the New-Keynesian literature.[31] The loan-to-value (LTV) ratio $\theta$ is set equal to 0.6. This is based on the long-run average of the cross-sectional mean LTV ratio for newly-built home mortgages and the share of conventional mortgages in total new loans. The amortization parameters $\kappa$ and $\alpha$ are set equal to 0.00162 and 0.9946, respectively. These values provide a reasonable approximation of the payment schedule for a 30-year mortgage. The bond market parameter $\vartheta$ is set equal to 0.035, in order to replicate an interest premium schedule for unsecured credit estimated by Chatterjee, Corbae, Nakajima and Rios-Rull (2007). The steady-state inflation rate $\pi$ is set equal to the aforementioned average of 0.0113. The weight on inflation $\nu_\pi$ in the monetary policy rule is set equal to 1.5, a standard value in the New-Keynesian literature.

[31] According to this parameterization, the average price duration is $(1-\psi)^{-1} = 3.33$ quarters, about 10 months.

### 5.2.2 Parameters calibrated jointly

Given the values of the parameters in the first set, the values of the six parameters in the second set ($\omega_1, \omega_2, \varrho, \epsilon_w, \tau_K, \overline{\tau}_2$) are determined by matching, in steady state, six targets: the observed average capital-to-output ratio ($K = 7.06$); housing stock-to-output ratio ($H = 5.28$); the aggregate hours worked ($N = 0.255$); capital owners' income share from labor ($\epsilon_w w n_1 / income_1 = 0.53$), mortgage debt servicing costs of homeowners ($\widetilde{m}_2 / income_2 = 0.15$); and homeowners' income share from transfers ($\tau_2 / income_2 = 0.12$). Here, $income_1 = (rk + \widetilde{m}_1) + \epsilon_w w n_1 + \tau_1$, $income_2 = w n_2 + \overline{\tau}_2$, and $\widetilde{m}_1 \equiv m_1/p$, $\widetilde{m}_2 \equiv m_2/p$, with $p$ normalized in steady state to equal to one. The expressions for income are consistent with the way income is defined in SCF. These targets yield $\omega_1 = 8.1616$, $\omega_2 = 13.004$, $\varrho = 0.6183$, $\epsilon_w = 2.4$, $\tau_K = 0.3362$, and $\overline{\tau}_2 = 0.0589$. Roughly speaking, $K$ identifies $\tau_K$, $H$ identifies $\varrho$, homeowners' income share from transfers identifies $\overline{\tau}_2$, and the aggregate labor $N$, capital owners' income share from labor, and mortgage debt servicing costs of homeowners identify the labor supply variables $\omega_1$, $\epsilon_w$, and $\omega_2$.

### 5.2.3 Discussion: the role of fiscal parameters

It is appropriate at this stage to explain why taxes and government expenditures are included in the model. Without taxes on capital and labor, positive transfers to homeowners would have to be financed by negative transfers to capital owners, which is inconsistent with the SCF data. Government expenditures in the model then ensure that, given the revenues from capital and labor taxes, the transfers to the two agents are not too large and thus do not account for too large shares of their income. Lining up the sources of income in the model with the data allows for realistic margins of income adjustment in smoothing out the effects of the real value of mortgage payments on disposable income.

### 5.2.4 Calibration based on model dynamics

Six parameters remain to be assigned values: $\zeta_K$, $\zeta_H$, $\rho_\mu$, $\rho_\eta$, $\sigma_\mu$, $\sigma_\eta$. These are calibrated on the basis of the model dynamics. Recall that we require the model to be consistent with both, the standard New-Keynesian responses to a monetary policy shock, discussed in Sections 3.1 and 3.2, and the empirical persistence of the FRM rate. The parameter $\rho_\mu$ is chosen so as to replicate the latter.[32] This yields $\rho_\mu = 0.99$. The parameters $\zeta_K$ and $\rho_\eta$ are chosen so as to replicate the typical New-Keynesian responses. In particular, the model is required to generate a one-percentage point (annualized) increase in the nominal interest rate accompanied with a -0.5 percent decline in output. Such quantitative responses, based on standard VARs, seem to roughly hold in both the United States and Eurozone data (e.g., Peersman and Smets, 2001). This strategy yields $\zeta_K = 4.5$ and $\rho_\eta = 0.3$. The value of $\rho_\eta$ is within the bounds of the persistence of standard monetary policy shocks, from 0 to 0.5, reported in the literature, depending on the model and the specification of the interest rate feedback rule.[33] The parameter $\zeta_H$ is then chosen so as to make housing investment about twice as volatile as capital investment, roughly in line with the data. This yields $\zeta_H = 5.0$. The calibration of $\sigma_\mu$ and $\sigma_\eta$ is postponed until Section 5.2.

## 5.3 Steady-state implications

Table 2 reports the steady-state values of the model's endogenous variables and, where possible, the long-run averages of their data counterparts. The first panel lists the variables used as calibration targets, while the second panel lists implications of the parameterization for other variables. As can be seen from the second panel, despite the stylized nature of the model, the steady state is broadly consistent with a number of moments not targeted in calibration. In particular, the model is consistent with the net rate of return on capital, the share of asset income in total income of capital owners, the share of labor income in total income of homeowners, and the distribution of earnings. Income distribution in the model prescribes somewhat larger share to capital owners than in the data. We also calculate mortgage payments, received (capital owner) or paid (homeowner), as a fraction of the agents' post-tax income. This fraction is much higher for the homeowner, 0.19, than for the capital owner, 0.07.

[32] 10-year government bond yield, rather than the 30-year FRM rate, is used due to longer data availability.

[33] The model is not rich enough to replicate the exact shape of the responses to the standard monetary policy shock obtained from the VARs. The calibration target is simply the sign and the relative size of the responses of the nominal interest rate and output. In the data, the decline in output is somewhat delayed, whereas in the model it is immediate.

# 6 Findings

The presentation of findings consists of two steps. First, we present the responses of the model economy to a one-percentage point (annualized) increase in the short-term nominal interest rate occurring due to either (i) the temporary or (ii) the persistent shock. In each case the responses are decomposed into the individual contributions of sticky prices (i.e., mortgages are removed by setting $\theta = 0$) and mortgages (i.e., prices are made fully flexible by setting $\psi = 0$). Second, we calibrate the relative sizes of the two shocks from yield curve data and use this information to assess the relative importance of the two shocks and the two frictions for the economy.

## 6.1 A one-percentage point increase in the short rate

The results of the first set of experiments confirm the arguments regarding the interaction between the frictions and the persistence of the shocks, developed analytically in Section 3, and their consequences for the aggregates and redistribution. These findings are presented in Figures 1-4.

Figure 1 shows the responses to the temporary shock under ARM. Under the baseline scenario with both sticky prices and mortgages, we can see the typical New-Keynesian responses that the model was calibrated to generate: the nominal interest rate increases while output and inflation fall, with the decline in output being larger than the decline in inflation. The decline in output is distributed across all of its components: consumption of both homeowners and capital owners, housing investment, and capital investment all decline in response to the shock. When the responses are decomposed into the effects of the individual frictions, it becomes apparent that they are driven by sticky prices. Mortgages are almost irrelevant. Their presence essentially only leads to a short-lived increase in real mortgage payments and thus somewhat stronger decline in consumption of homeowners than is the case otherwise. Effectively the same message comes out also from the responses under FRM, as Figure 2 shows. Here, even the response of homeowners' consumption is almost identical with or without mortgages, as the temporary shock under FRM has very limited effect on real mortgage payments.

Figures 3 and 4 report the responses, under ARM and FRM, to the level-factor shock. First, observe that in both cases, by the nature of the shock, the nominal interest rate and inflation increase almost one-for-one and that their responses are highly persistent. Further, in line with our discussion in Section 3, real mortgage payments increase immediately and persistently under ARM, whereas under FRM they exhibit a protracted decline. Notice also that, in accordance with the intuition developed in Section 3, the size of the initial increase in real mortgage payments under ARM is essentially the same (about 6%) as in the case of the temporary shock. In both cases the nominal interest rate increases, on impact, by one percentage point per annum. In the previous case this was due to an increase in the real rate, whereas in the present case it is due to an increase in the inflation rate. In the present case, however, the increase in real mortgage payments is substantially more persistent.

The two figures also show the redistributive nature of the shock. Under ARM, in response to the sharp increase in real mortgage payments, consumption of homeowners declines. Housing investment, which is in addition negatively affected by more expensive new loans (the price effect), also declines, thus reducing future housing services. In contrast, consumption of capital owners, as well as capital investment, increase. Aggregate responses, measured by the responses of aggregate output and consumption, are, however, small (as total investment is the difference between output and total consumption, it also responds only a little). Decomposition into the contribution of the individual frictions shows that most of the responses of consumption by the two agents (as well as of housing investment) are due to mortgages. In fact, the redistributive consequences for homeowners would be even larger if sticky prices were not present. This is because positive inflation under sticky prices somewhat increases output and thus also homeowners' income and consumption.

The message under FRM (Figure 4) is similar to that under ARM. The main effect of the level-factor shock is redistributive and redistribution occurs due to mortgages. The difference, compared with the ARM case, is that the redistribution is in favor of homeowners and that the redistributive effects are gradual, as expected from our discussion in Section 3.

# 7 Conclusion

The presence of nominal rigidities is an important element in the transmission mechanism of monetary policy. For a number of developed economies, yield curve data show that fluctuations in nominal interest rates, including the short rate that is under an effective control of monetary policy, are well captured by two distinct components. One is relatively temporary whereas the other is highly persistent. Such changes in the policy interest rate can potentially generate both aggregate as well as redistributive effects in the economy, in particular when borrowers and lenders use long-term nominal contracts, such as mortgages, and products markets are not fully flexible.

Using a dynamic stochastic general equilibrium model, we compare the quantitative importance of such nominal rigidities, sticky prices and long-term mortgage contracts, in transmitting temporary and persistent changes in the policy rate into the real economy. Sticky prices have been at the core of models used for monetary policy analysis for nearly two decades, while the interest in nominal debt contracts is more recent. Our model indicates that the sticky price channel is the more important transmission mechanism for temporary changes in the policy rate, whereas the mortgage channel is powerful when the changes are persistent. The real effects of the two channels, however, manifest themselves differently. The rigidities in product markets generate significant aggregate effects but small redistributive effects. The opposite holds for the transmission through mortgages. Simulating the economy shows that the redistributive consequences of monetary policy operating through the mortgage channel are of similar magnitudes as the standard aggregate consequences operating through the sticky price channel. The size of the redistribution is not affected by the nature of the debt contract (ARM vs. FRM), although the timing and direction is. Furthermore, consumption of homeowners (borrowers) is affected significantly more than consumption of lenders.

In terms of policy implications for central banks, the model suggests that while persistent changes in the policy rate have a small impact on aggregate economic activity, they generate sizeable redistributions in mortgage markets. This lesson is especially pertinent in the current policy environment, in which nominal interest rates have been kept at low levels for almost a decade. The purpose of such policies was to stimulate aggregate economic activity. According to our model, the initial cut in policy rates may have fulfilled this objective, to the extent it was expected to be temporary, but the subsequent policy of keeping rates low for a substantial period of time more likely led to income and consumption redistribution than to the desired aggregate effects. As inflation followed nominal interest rates to similarly low levels, based on our model, we can infer that lenders in FRM countries gained at the expense of borrowers due to persistently low inflation rates, while in ARM countries borrowers gained at the expense of lenders due to persistently low nominal interest rates.

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Table 1: Parameter values

| Symbol | Value | Description |
|---|---|---|
| **Population** | | |
| $\Psi$ | 2/3 | Share of homeowners |
| **Preferences** | | |
| $\beta$ | 0.9883 | Discount factor |
| $\sigma_1$ | 1.0 | Frisch elasticity (capital owner) |
| $\sigma_2$ | 1.0 | Frisch elasticity (homeowner) |
| $\omega_1$ | 8.1616 | Disutility from labor (capital owner) |
| $\omega_2$ | 13.004 | Disutility from labor (homeowner) |
| $\varrho$ | 0.6183 | Weight on consumption (homeowner) |
| **Technology** | | |
| $\varsigma$ | 0.283 | Capital share of output |
| $\Delta$ | 0.2048 | Fixed cost |
| $\delta_K$ | 0.02225 | Depreciation rate of capital |
| $\delta_H$ | 0.01021 | Depreciation rate of housing |
| $\epsilon_w$ | 2.4 | Rel. productivity of cap. owners |
| $\zeta_K$ | 4.5 | Curvature of PPF ($X_K$) |
| $\zeta_H$ | 5.0 | Curvature of PPF ($X_H$) |
| **Fiscal** | | |
| $G$ | 0.138 | Government expenditures |
| $\tau_N$ | 0.235 | Labor income tax rate |
| $\tau_K$ | 0.3362 | Capital income tax rate |
| $\overline{\tau}_2$ | 0.0589 | Transfer to homeowner |
| **Goods market** | | |
| $\varepsilon$ | 0.83 | Elasticity of substitution |
| $\psi$ | 0.7 | Fraction not adjusting prices |
| **Mortgage market** | | |
| $\theta$ | 0.6 | Loan-to-value ratio |
| $\kappa$ | 0.00162 | Initial amortization rate |
| $\alpha$ | 0.9946 | Amortization adjustment factor |
| **Bond market** | | |
| $\vartheta$ | 0.035 | Participation cost function |
| **Monetary policy** | | |
| $\pi$ | 0.0113 | Steady-state inflation rate |
| $\nu_\pi$ | 1.5 | Weight on inflation |
| **Exogenous processes** | | |
| $\rho_\mu$ | 0.99 | Persistence of the level factor shock |
| $\rho_\eta$ | 0.3 | Persistence of standard mon. pol. shock |

Table 2: Nonstochastic steady state vs long-run averages of U.S. data

| Symbol | Model | Data | Description |
|---|---|---|---|
| **Targeted in calibration:** | | | |
| $i^M$ | 0.0233 | 0.0233 | Nominal mortgage rate |
| $X_K$ | 0.156 | 0.156 | Capital investment |
| $X_H$ | 0.054 | 0.054 | Housing investment |
| $K$ | 7.06 | 7.06 | Capital stock |
| $H$ | 5.28 | 5.28 | Housing stock |
| $N$ | 0.255 | 0.255 | Aggregate hours worked |
| $\epsilon_w wn_1/income_1$ | 0.53 | 0.53¶ | Labor income in cap. owners' income |
| $\widetilde{m}_2/(wn_2+\overline{\tau}_2)$ | 0.15 | 0.15 | Debt-servicing costs (pre-tax) |
| $\overline{\tau}_2/(wn_2+\overline{\tau}_2)$ | 0.12 | 0.12¶ | Transfers in homeowners' income |
| **Not targeted:** | | | |
| **A.** Capital owner's variables | | | |
| $(1-\tau_K)(r-\delta_K)$ | 0.012 | 0.013§ | Net (post-tax) rate of return on capital |
| $[(r-\delta)k+\widetilde{m}_1]/income_1$ | 0.42 | 0.39¶,§§ | Income from assets in total income |
| $\tau_1/income_1$ | 0.05 | 0.08 | Transfers in total income |
| $\widetilde{m}_1/netincome_1$ | 0.07 | N/A | Mortg. income in post-tax income |
| **B.** Homeowner's variables | | | |
| $wn_2/(wn_2+\tau_2)$ | 0.88 | 0.82¶ | Labor income in total income |
| $\tau_H$ | 0 | N/A | Housing wedge |
| $\widetilde{m}_2/[(1-\tau_N)wn_2+\tau_2]$ | 0.19 | N/A | Debt-servicing costs (post-tax) |
| **C.** Earnings distribution | | | |
| $\epsilon_w wN_1/[\epsilon_w wN_1+wN_2]$ | 0.60 | 0.54¶ | Capital owners' share |
| $wN_2/[\epsilon_w wN_1+wN_2]$ | 0.40 | 0.46¶ | Homeowners' share |
| **D.** Income distribution | | | |
| $Income_1/[Income_1+(wN_2+\Psi\tau_2)]$ | 0.70 | 0.60¶ | Capital owners' share |
| $(wN_2+\Psi\tau_2)/[Income_1+(wN_2+\Psi\tau_2)]$ | 0.30 | 0.40¶ | Homeowners' share |

**Notes.** $Y = 1$ in steady state. Capital owner's income: $income_1 = (rk + \widetilde{m}_1) + \epsilon_w wn_1 + \tau_1$; $Income_1 = (1-\Psi)income_1$; and $netincome_1 = ((1-\tau_K)rk + \tau_K\delta_K k + \widetilde{m}_1) + (1-\tau_N)\epsilon_w wn_1 + \tau_1$. Rates of return, interest, and amortization rates are expressed at quarterly rates.

¶ SCF; the model counterpart is defined so as to be consistent with the definition in SCF.

‡ Average for a standard 30-year mortgage.

§ NIPA-based estimate (Gomme, Ravikumar and Rupert, 2011).

§§ The sum of capital and business income in SCF, where capital income is income from all financial assets.

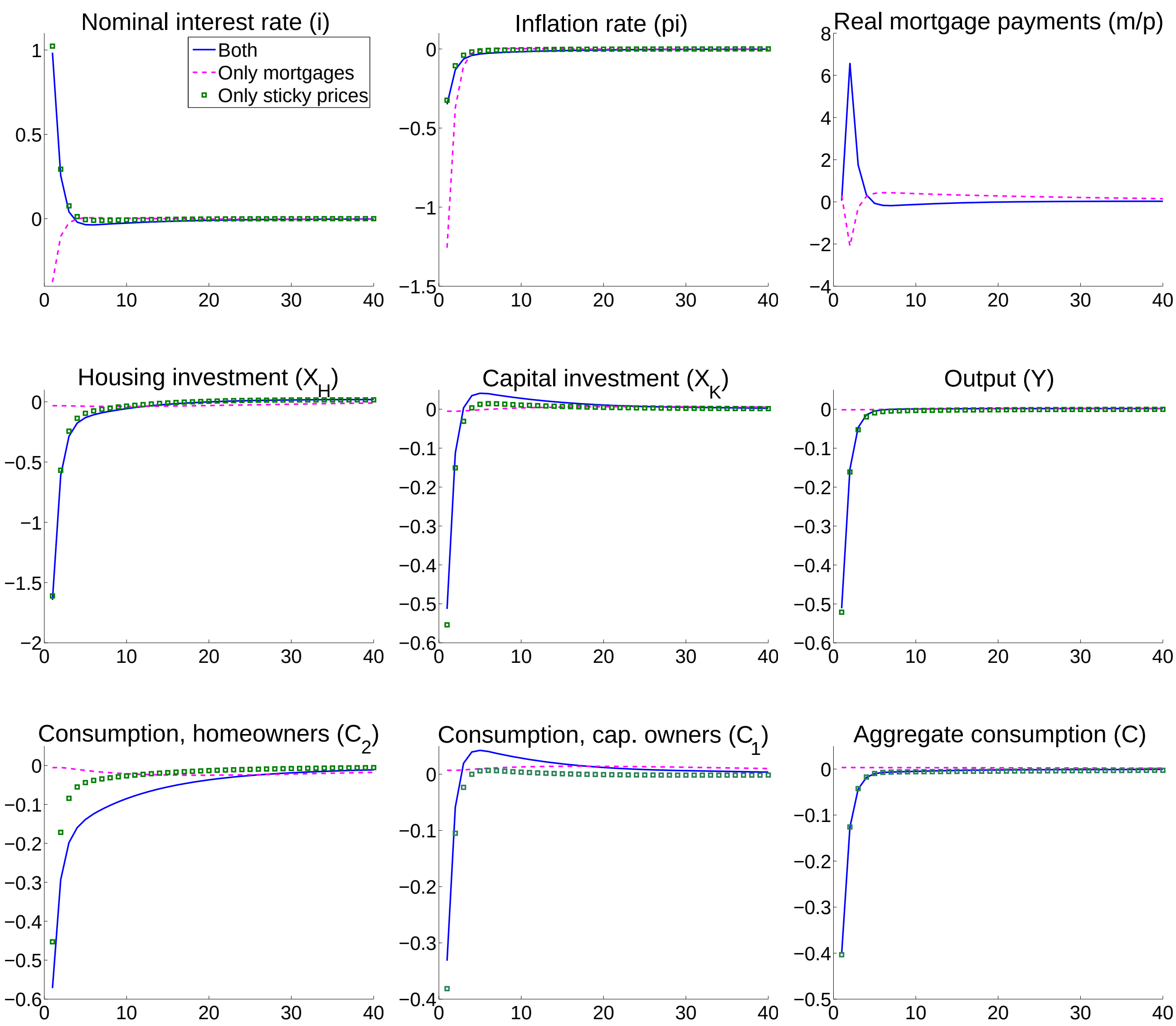



Figure 1: ARM; responses to the standard monetary policy shock. Interest rates and the inflation rate are measured as percentage point (annualized) deviations from steady state, quantities are in percentage deviations. One period = one quarter.

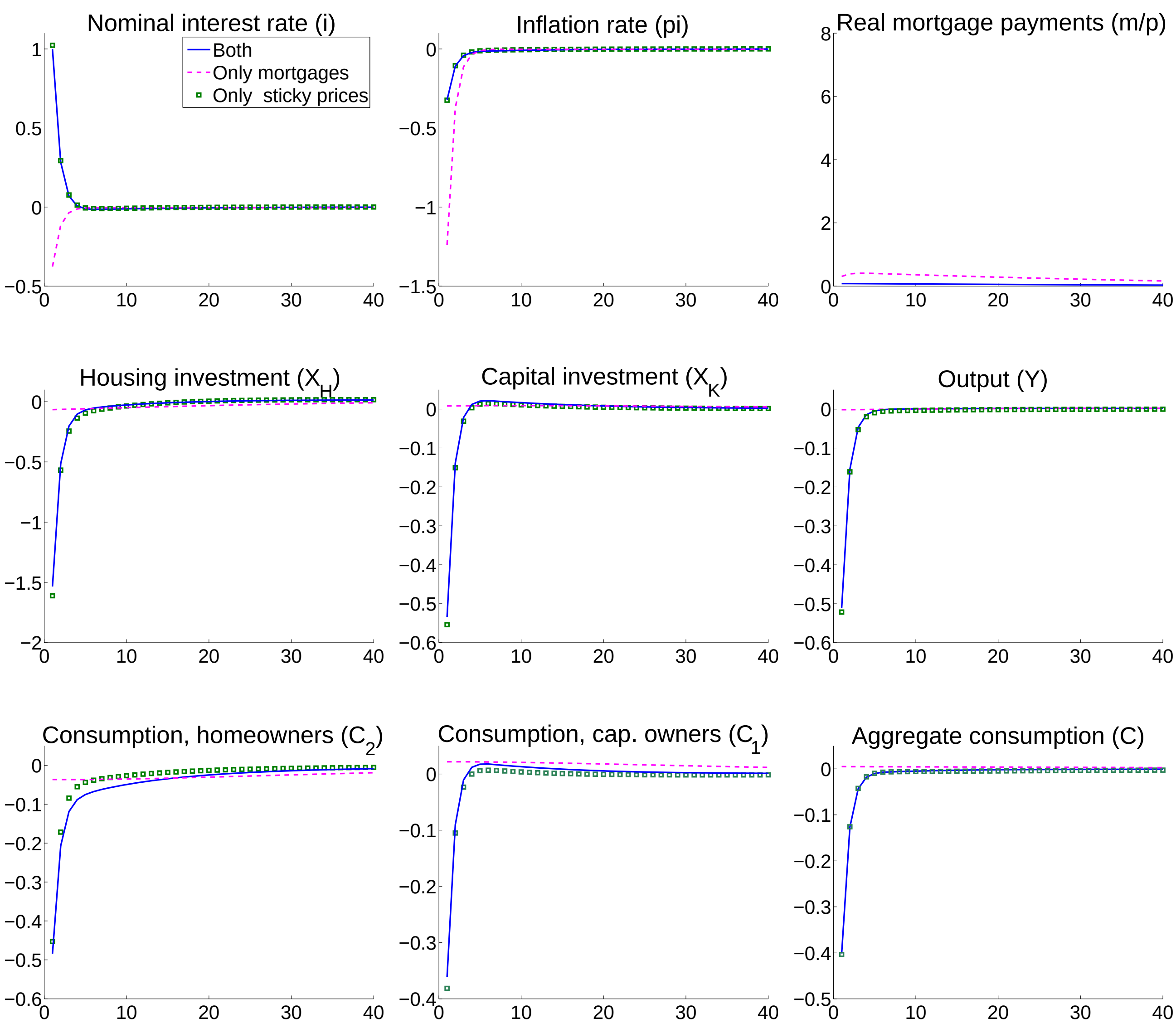



Figure 2: FRM; responses to the standard monetary policy shock. Interest rates and the inflation rate are measured as percentage point (annualized) deviations from steady state, quantities are in percentage deviations. One period = one quarter.

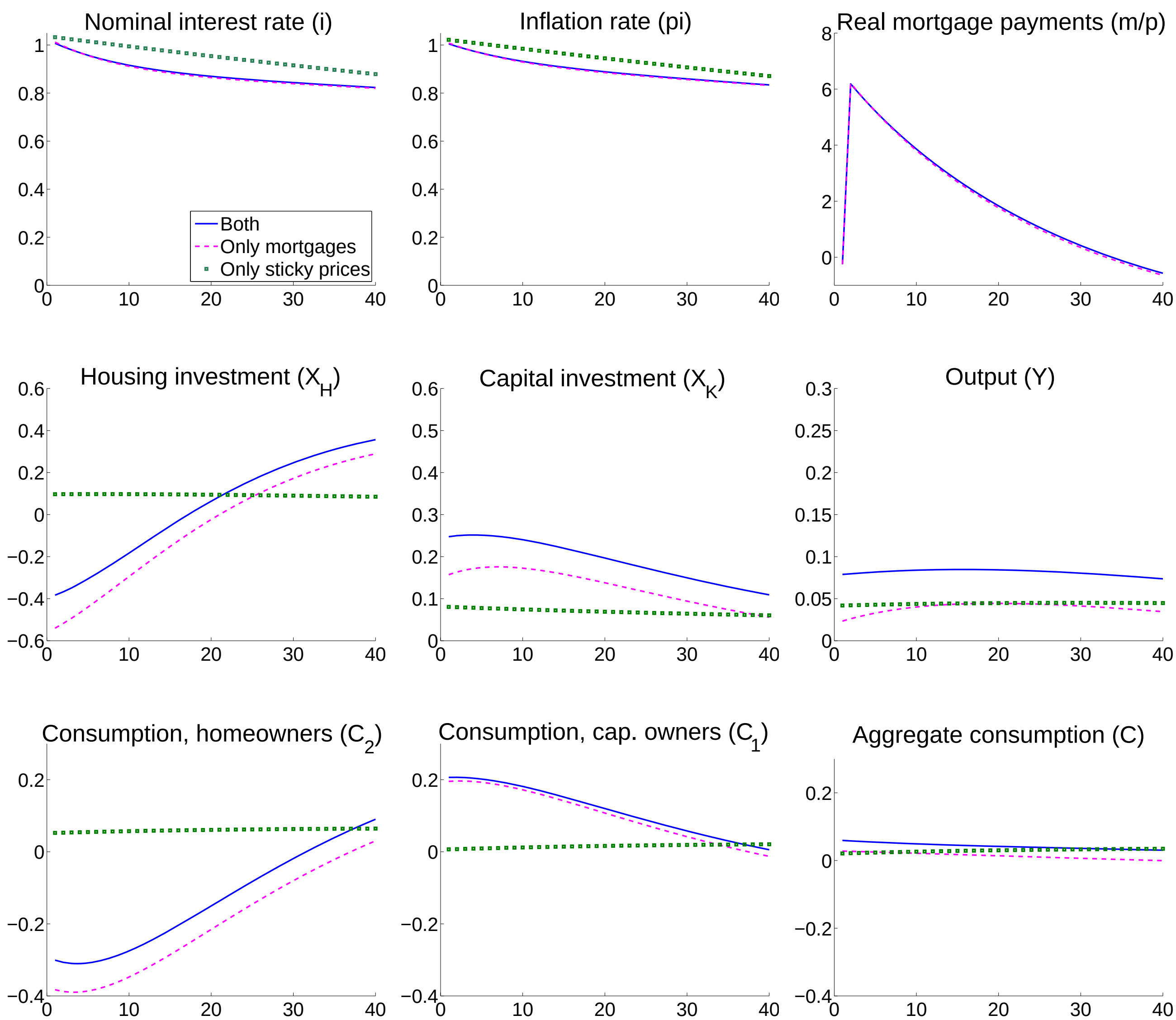



Figure 3: ARM; responses to the level factor shock. Interest rates and the inflation rate are measured as percentage point (annualized) deviations from steady state, quantities are in percentage deviations. One period = one quarter.

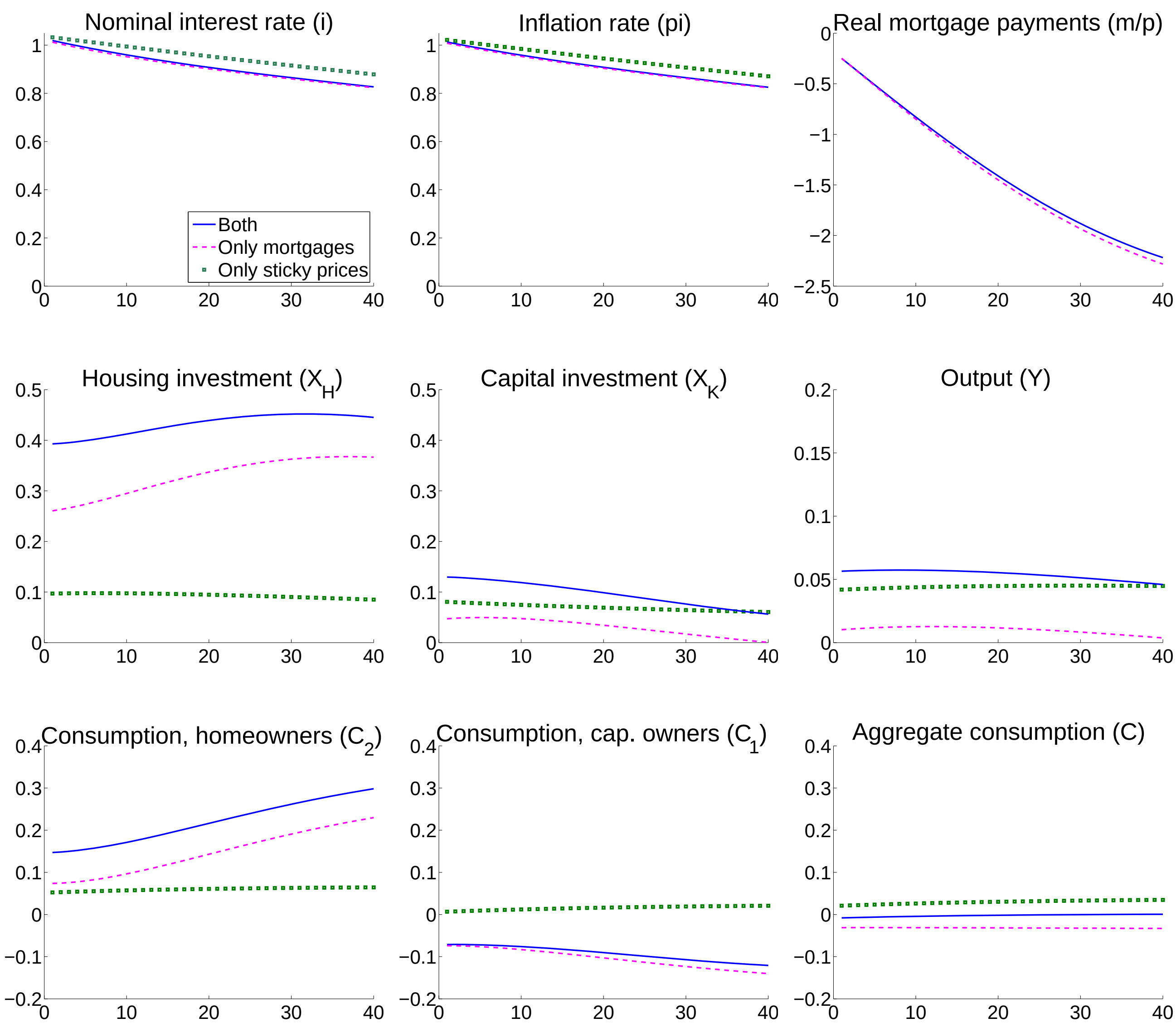



Figure 4: FRM; responses to the level factor shock. Interest rates and the inflation rate are measured as percentage point (annualized) deviations from steady state, quantities are in percentage deviations. One period = one quarter.

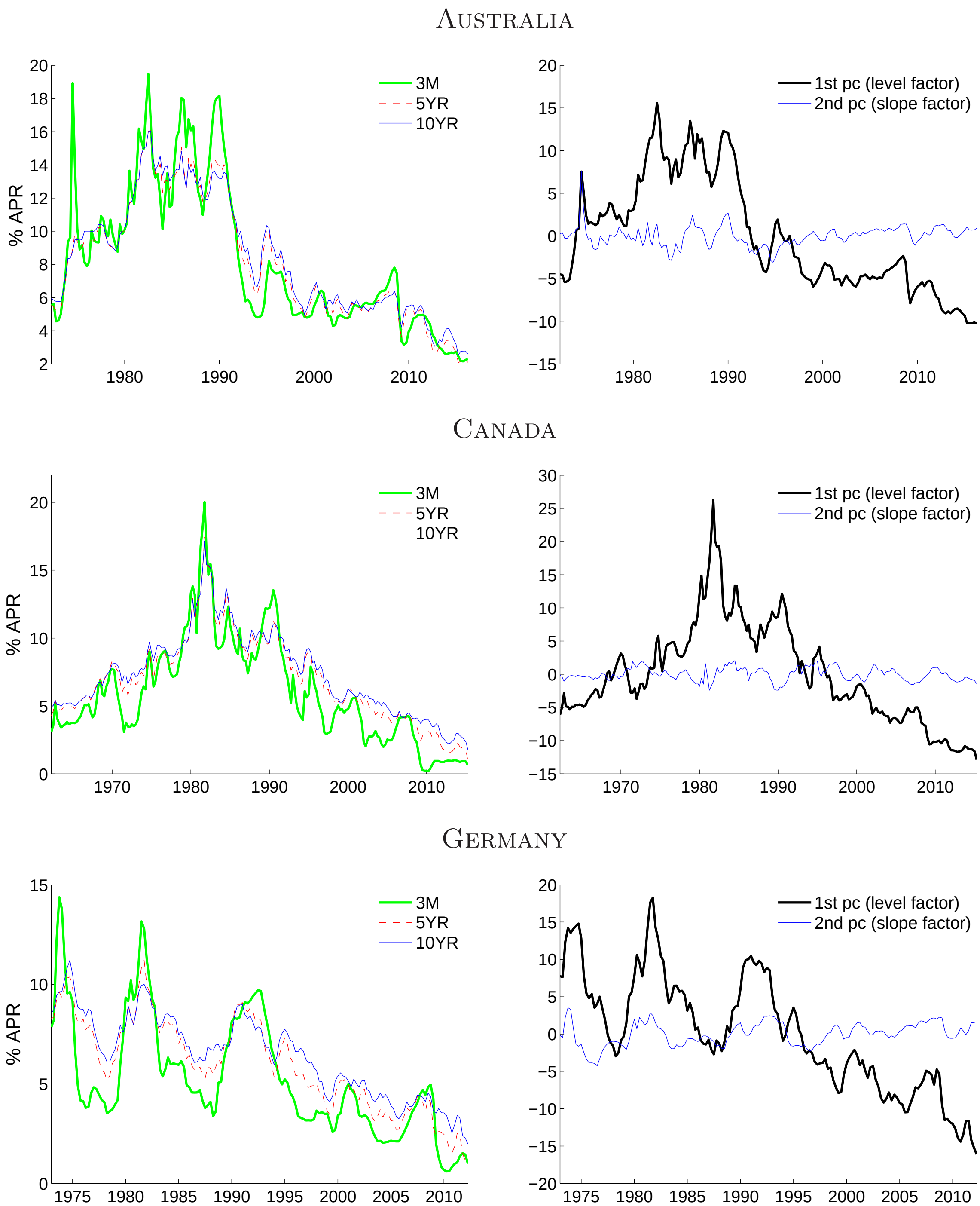
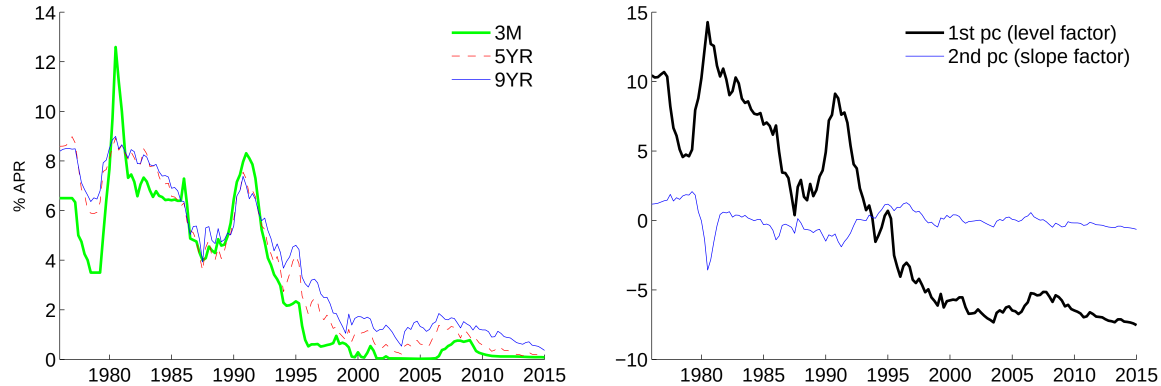



Figure 5: Nominal interest rates and principal components. Note: Only selected maturities used in the principal component analysis are plotted in the left-hand side charts (see the text for a complete list of maturities used).

## Japan




## United States

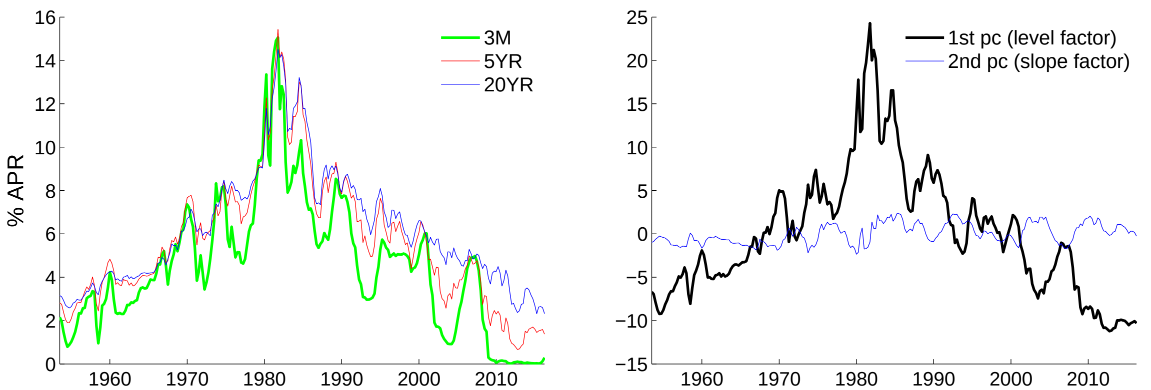



Figure 6: Nominal interest rates and principal components (continued). Note: Only selected maturities used in the principal component analysis are plotted in the left-hand side charts (see the text for a complete list of maturities used).

Table 3: Statistical properties of the 1st principal component (level factor)

| | $\frac{\text{std(1st pc)}}{\text{std(2nd pc)}}$ | % var($ylds$) expl. | acorr | corr w/ short | corr w/ long | corr w/ infl. |
|---|---|---|---|---|---|---|
| AUS | 5.49 | 0.97 | 0.98 | 0.98 | 0.98 | 0.67 |
| CAN | 7.69 | 0.98 | 0.98 | 0.98 | 0.98 | 0.72 |
| GER | 5.02 | 0.96 | 0.98 | 0.93 | 0.97 | 0.80 |
| JAP | 7.92 | 0.98 | 0.99 | 0.97 | 0.99 | 0.77 |
| US | 6.22 | 0.97 | 0.98 | 0.98 | 0.97 | 0.73 |

Table 4: Quantitative assessment of the shocks/frictions

| | ARM | | | FRM | | |
|---|---|---|---|---|---|---|
| | 100 × std $\mu$ and $\eta$ | % var only $\mu$ | % var only $\eta$ | 100 × std $\mu$ and $\eta$ | % var only $\mu$ | % var only $\eta$ |
| $i$ | 0.77 | 0.95 | 0.05 | 0.77 | 0.95 | 0.05 |
| $C$ | 0.32 | 0.22 | 0.78 | 0.25 | 0.04 | 0.96 |
| $C_1$ | 0.52 | 0.80 | 0.20 | 0.54 | 0.82 | 0.18 |
| $C_2$ | 1.21 | 0.83 | 0.17 | 1.33 | 0.93 | 0.07 |
| $C_{2,total}$ | 0.97 | 0.88 | 0.12 | 1.12 | 0.96 | 0.04 |
| $X$ | 1.22 | 0.55 | 0.45 | 1.08 | 0.53 | 0.47 |
| $X_K$ | 0.66 | 0.72 | 0.28 | 0.43 | 0.39 | 0.61 |
| $X_H$ | 1.79 | 0.60 | 0.40 | 1.85 | 0.71 | 0.29 |
| $Y$ | 0.45 | 0.40 | 0.60 | 0.37 | 0.24 | 0.76 |
| | corr $\mu$ and $\eta$ | corr only $\mu$ | corr only $\eta$ | corr $\mu$ and $\eta$ | corr only $\mu$ | corr only $\eta$ |
| $C_1, C_2$ | -0.61 | -0.89 | 0.65 | -0.78 | -0.99 | 0.77 |

**Note.** The moments are for the stationary distribution of the endogenous variables. The $\mu_t$ (level factor) shock transmits mainly through mortgages whereas the $\eta_t$ (standard monetary policy) shock transmits only through sticky prices. The interest rate (APR/400) is measured as a percentage point deviation from steady state, quantities as percentage deviations from steady state. Agent 1 = capital owner, agent 2 = homeowner. $C_{2,total} = C_2^{\varrho} H^{1-\varrho}$.