EUROJÄRJESTELMÄ
EUROSYSTEMET

Centre for Economic Policy Research

7th Annual Bank of Finland/CEPR Conference:

Credit and the Macroeconomy

Hosted by the Bank of Finland

Helsinki, 2-3 November 2006

The Role of Housing Collateral in an Estimated Two-Sector Model of the U.S. Economy

Matteo Iacoviello and Stefano Neri

The organizers would like to thank the Bank of Finland for hosting this event.

The views expressed in this paper are those of the author(s) and not those of the funding organization(s) nor of CEPR which takes no institutional policy positions.

The Role of Housing Collateral in an Estimated Two-Sector Model of the U.S. Economy

Matteo Iacoviello* Stefano Neri†
Boston College Bank of Italy

October 23, 2006

Abstract

We investigate the ability of a two-sector model to quantify the role of the housing market in business fluctuations. We use US data to estimate the structural parameters of the model via maximum likelihood methods. We find robust empirical support for feedback effects from housing to the rest of the economy, mostly working through the effects on non-durable consumption that spill over - through collateral effects - from shocks in the housing sector.

We use the estimated model to address three questions: (1) What has been the contribution of the housing boom in the post 9/11 recovery? (2) What would have happened had the Fed tried to stabilize house prices? (3) How have financing frictions evolved over time?

[VERY PRELIMINARY. COMMENTS WELCOME]

1. Introduction

The role of the housing market in business fluctuations has gained increased attention among academics and policymakers in recent years. On the one hand, this reflects the observation that, while central bankers have won the battle for price stability, large fluctuations in asset values are still common and far from understood in many developed economies. On the other, this reflects the consideration that developments in the housing market seem to have broader macroeconomic consequences: for instance, the rise in housing valuations in the United States at the turn of the century not only seems to have driven up residential investment, but, through home equity extraction, has been cited as one of the driving forces behind the high consumption growth of the last years.[1]

However, while academic and policy debates often focus on the importance of the housing market, the new generation of business cycle models that has been become popular in monetary policy analysis largely abstracts from housing altogether. To fill this gap, we develop and estimate

*Email: iacoviel@bc.edu. Address: Boston College, Department of Economics, Chestnut Hill, MA, 02467, USA.
†Email: stefano.neri@bancaditalia.it. Address: Banca d'Italia, Research Department, Via Nazionale 91, I-00184 Roma, Italy.

[1] See for instance a recent quote from the Fed Chairman Greenspan (2005): "[I]t is difficult to dismiss the conclusion that a significant amount of consumption is driven by capital gains on some combination of both stocks and residences, with the latter being financed predominantly by home equity extraction".

using a Bayesian likelihood approach a small-scale dynamic stochastic general equilibrium model for the US economy that explicitly models the housing market.[2] We do so with three main goals in mind. First, we want to understand the extent to which a model with nominal and real rigidities and credit frictions can explain the dynamics of residential investment and housing prices that are observed in the data. Second, we want to measure the feedback effects going from the housing market to the rest of the economy. Third, because we rely on a model which is structurally estimated and robust to the Lucas' critique, we can address policy questions, conduct counterfactuals, and make quantitative statements.

In modeling housing, our starting point is a variant of many small-scale monetary business cycle models that have become popular in monetary policy analysis. We depart from this framework in two important and distinct ways. On the supply side, our model features two sectors: the non-housing sector, featuring nominal rigidities, produces consumption and business fixed investment; the housing sector, featuring flexible prices produces residential investment.[3] On the demand side, residential capital enters the utility function and can be used as a collateral for loans by a fraction of households that are subject to borrowing constraints (crucially, we let the data decide how large the fraction of is). Because new housing and consumption goods are produced using different technologies, the model endogenously generates heterogeneous dynamics both in residential vis-à-vis nonresidential investment and in the relative price of housing. At the same time, fluctuations in the price of housing affect the borrowing capacity of a fraction of households, on the one hand, and the relative profitability of producing new homes, on the other: such effects generate implications for the feedback of housing prices on other forms of expenditure.

Our main results can be summarized as follows: we find robust empirical support for feedback effects from housing to the rest of the economy, mostly working through the effects on non-durable consumption that spillover - through collateral effects - from shocks in the housing sector. We are able to quantify the contribution to consumption of the recent housing boom, and to show that, had the Fed tried to stabilize house prices, this would have had dramatic negative consequences on the economy.

In the next section, we discuss our model. In section three, we discuss the calibration, the data and the prior distribution of the structural parameters of the model and of the shock processes. In section four, we present our estimates. In section five, we use the estimated model to discuss a number of keys issues related to the role of the housing market in the business cycle. In section six, we discuss results based on a sticky-wage extension of our model. Section seven relates our paper

[2] Using a simulated method of moments approach, Iacoviello (2005) estimates a monetary business cycle model with housing, nominal loans and collateral constraints. His main focus is on the effects of collateral price shocks on consumption, but he assumes that the stock of aggregate housing is fixed, thus shutting off the links between aggregate residential investment and economic activity.

[3] Barsky, House and Kimball (2006) note several reasons why housing might have flexible prices. First, housing is relatively expensive on a per-unit basis; therefore, if menu costs have important fixed components, there is a large incentive to negotiate on the price of this good. Second, most homes are priced for the first time when they are sold.

to the literature, and section eight concludes.

2. The model

The model features two production sectors, heterogeneity in households' discount factors and collateral constraints tied to a fraction of housing values.

On the purchasers' side, there are two types of households, patient (lenders) and impatient (borrowers). Patient households work, consume and accumulate housing: they own the productive capital of the economy, supply loanable funds to firms on the one hand, and to impatient households on the other. Impatient households work, consume and accumulate housing: because they have a high propensity to dissave, they are up against their maximum borrowing limit in equilibrium.

On the producers' side, there are two sectors. The non-housing sector combines capital and labor to produce consumption and business capital for both sectors. The housing sector produces new homes, combining business capital with labor and land. Each household allocates hours worked across the two sectors. We allow for (but do not impose) Calvo-style price rigidities in the non-housing sector. Similarly, we allow for the share of impatient households to take on any value on the unit interval: to the extent that the impatient group becomes arbitrarily small, our model boils down to a representative agent model.

2.1. Households

Patient and impatient households respectively maximize the expected present value of lifetime utility as given by:[4]

$$E_0 \sum_{t=0}^{\infty} (\beta g_C)^t \, \mathsf{z}_t \left(\log (c_t - \varepsilon g_C c_{t-1}) + \mathsf{j}_t \log h_t - \tau_t \left(n_{ct}^{1-\nu} + n_{ht}^{1-\nu} \right)^{\frac{1+\eta}{1-\nu}} \right) \quad (1)$$

$$E_0 \sum_{t=0}^{\infty} \left(\beta' g_C\right)^t \, \mathsf{z}_t \left(\log \left(c'_t - \varepsilon' g_C c'_{t-1} \right) + \mathsf{j}_t \log h'_t - \tau_t \left(\left(n'_{ct}\right)^{1-\nu'} + \left(n_{ht}\right)^{1-\nu'} \right)^{\frac{1+\eta'}{1-\nu'}} \right) \quad (2)$$

where variables without a prime denote the patient, variables with a prime denote the impatient, and c_t, h_t, n_{ct}, n_{ht} represent consumption, housing, hours worked in the consumption sector and hours worked in the construction sector. The discount factors are β and β', E is the expectation operator and g_C is the trend growth rate of consumption along the balanced growth path. Random variations in z_t, j_t and τ_t proxy respectively for aggregate demand, housing demand, and labor

[4] We assume a cashless limit in the sense of Woodford (2003), so that the role of money in transactions becomes negligible, but the price level is still meaningful as a rate of exchange between interest bearing private debt and real goods.

supply shocks. These shocks are assumed to follow stationary autoregressive processes of the form:

$$\begin{aligned}
\ln z_t &= \rho_z \ln z_{t-1} + \varepsilon_{zt},\ \varepsilon_{zt} \sim N(0, \sigma_z) \\
\ln j_t &= \left(1-\rho_j\right) \ln j + \rho_j \ln j_{t-1} + \varepsilon_{jt},\ \varepsilon_{jt} \sim N(0, \sigma_j) \\
\ln \tau_t &= \rho_\tau \ln \tau_{t-1} + \varepsilon_{\tau t},\ \varepsilon_{\tau t} \sim N(0, \sigma_\tau).
\end{aligned}$$

The specification of the disutility of labor follows Horvath (2000), in assuming that the household has a preference for diversity of labor across sectors. This allows capturing through the parameter ν some degree of sector specificity, so long as ν is smaller than zero.

The upshot of having different discount rates is that, so long as β' is lower than β, impatient agents decumulate wealth quickly enough to some lower bound. For small fluctuations around the steady state, the lower bound is always binding. It then follows that patient agents will own and accumulate all the capital in a neighborhood of the steady state, whereas impatient agents' only form of wealth will be their home, and they will borrow the maximum possible amount against it.

We use a decentralization of our model with the following features.[5] Patient agents save by purchasing capital, homes and making loans to impatient agents; in the following period, they rent capital to firms and sell the undepreciated capital; in addition, there is joint production of consumption and business investment goods, with A_k representing the relative marginal cost of producing capital in the consumption good sector in terms of consumption.[6]

Patient agents maximize 1 subject to the following sequence of budget constraints (using consumption as the numeraire):

$$\begin{aligned}
& c_t + \frac{k_{ct}}{\mathsf{A}_{kt}} + k_{ht} + q_t\left(h_t - (1-\delta_h) h_{t-1}\right) + p_{lt}\left(l_t - l_{t-1}\right) = w_{ct} n_{ct} + w_{ht} n_{ht} \\
& + \left(R_{ct} + \frac{1-\delta_k}{\mathsf{A}_{kt}}\right) k_{ct-1} + \left(R_{ht} + 1 - \delta_k\right) k_{ht-1} + b_t - \frac{R_{t-1} b_{t-1}}{\pi_t} + R_{lt} l_{t-1} + f_t - \phi_t \qquad (3)
\end{aligned}$$

where $\pi_t = P_t / P_{t-1}$ is the gross inflation rate between period $t-1$ and t, f_t denotes profits from ownership of finished good firms, and ϕ_t denotes standard quadratic adjustment costs for capital.[7] Patient agents choose plans for consumption c_t, capital in the consumption-good sector k_c, capital in the housing sector k_h, housing h_t (priced at q_t), land holdings l_t (priced at p_{lt}), hours in both sectors n_{ct} and n_{ht} and one-period loans b_t to maximize their utility subject to the constraint above. The term A_{kt} captures investment-specific technological shocks, whose stochastic properties are described below. Loans b_t are set in nominal terms, yield a gross, riskless nominal return of R_t, but are subject to inflation risk. Real wages in each sector are denoted by w_i, real rental rates by

[5] An analogous decentralization is used by Greenwood, Hercowitz and Krusell (2000).

[6] We assume that investment-specific technological change applies only to k_c, the capital used in the production of consumption goods, since investment-specific technological progress mostly refers to information technology (IT), and construction is a non-IT-intensive industry.

[7] That is:

$$\phi_t = \frac{\phi_{kc}}{2}\left(\frac{k_{ct} - k_{ct-1}}{k_{ct-1}}\right)^2 k_{ct-1} + \frac{\phi_{kh}}{2}\left(\frac{k_{ht} - k_{ht-1}}{k_{ht-1}}\right)^2 k_{ht-1}$$

R_i, depreciation rates by δ_i. The first-order conditions for their problem are somewhat standard: we report them in Appendix B.

Impatient agents maximize 2 subject to two constraints. Their flow wealth constraint is analogous to the constraint of the lenders, with the exception that they do not purchase capital, do not own finished good firms, and do not own land. In addition, the maximum amount they can borrow is given by the expected present value of their home, times the loan-to-value ratio m:

$$c'_t + q_t \left(h'_t - (1-\delta_h) h'_{t-1}\right) = w'_{ct} n'_{ct} + w'_{ht} n'_{ht} + b'_t - \frac{R_{t-1}}{\pi_t} b'_{t-1} \tag{4}$$

$$b'_t \leq m E_t \left(q_{t+1} h'_t \pi_{t+1} / R_t\right). \tag{5}$$

The assumption $\beta' < \beta$ implies that for small shocks the borrowing constraint 5 will hold with equality in a neighborhood of the steady state. The first order conditions are in Appendix B.

2.2. Technology and intermediate goods firms

A representative firm takes input prices as given, hires labor and rents capital to produce intermediate goods Y_t and new homes IH_t in order to maximize profits:[8]

$$\max \frac{Y_t}{X_t} + q_t IH_t - \left(\sum w_{it} n_{it} + R_{ct} k_{ct-1} + R_{ht} k_{ht-1} - R_{lt} l_{t-1}\right).$$

In the formulation above, we define X_t as the markup of final over intermediate goods. We assume that the intermediate goods (nominal price P_t^w) are transformed into final goods (priced at P_t) from final goods firms (described below). The production technologies are:

$$Y_t = \left(\mathsf{A}_{ct} \left(n_{ct}^{\alpha} n_{ct}'^{1-\alpha}\right)\right)^{1-\mu_c} k_{ct-1}^{\mu_c} \tag{6}$$

$$IH_t = \left(\mathsf{A}_{ct} \mathsf{A}_{ht} \left(n_{ht}^{\alpha} n_{ht}'^{1-\alpha}\right)\right)^{1-\mu_h-\mu_l} k_{ht-1}^{\mu_h} l_{t-1}^{\mu_l}. \tag{7}$$

Here, A_{ct} is a measure of neutral, aggregate productivity, whereas A_{ht} is a measure of sector-specific productivity in the $IH-$sector, described below.[9]

The first order conditions are standard (see Appendix B). Out of pure convenience, we allow for the hours of the two groups to enter the two production technologies in a Cobb-Douglas fashion: this allows us obtaining closed form solutions for the steady state of the model; in this formulation, $1-\alpha$ measures the labor income share of credit-constrained households.[10]

[8] Due to the constant-returns-to-scale assumption, the intermediate goods firm makes zero profits in each period.

[9] Our formulation implicitly assumes that the volatility of the innovations in the housing sector is bounded below by the volatility of innovations in the non-housing sector. The data offers ample support for this formulation; we tried an alternative specification dropping A_{ct} from the production function for housing, and allowing for correlation between A_{ct} and A_{ht}. The results were virtually identical to those that we present here.

[10] We have also experimented with an alternative setup in which the hours of the groups are perfect substitutes in production. The results were similar to those that we report here for our Cobb-Douglas case.

2.3. Final good firms and monetary policy

We motivate sticky prices in the consumption-business fixed investment sector by assuming monopolistic competition at the "retail" level and implicit costs of adjusting nominal prices following Calvo-style contracts. Retailers buy intermediate goods Y_t from intermediate firms at the price P_t^w in a competitive market, differentiate the goods at no cost, and sell them at a markup over the marginal goods. The CES aggregates of these goods are then converted back into homogeneous consumption and investment goods by households. In each period, a fraction $1-\theta_\pi$ of retailers sets prices optimally; a fraction θ_π cannot reset their prices optimally, and indexes prices to the previous period inflation rate with an elasticity equal to ι_π, as in Smets and Wouters (2003). It is then possible to obtain a new-keynesian Phillips curve in the consumption good sector of the form (expressed in log deviations from the zero inflation steady state):

$$\log \pi_t - \iota_\pi \log \pi_{t-1} = \beta g_C \left(E_t \log \pi_{t+1} - \iota_\pi \log \pi_t \right) - \varepsilon_{\pi X} \log \left(\frac{X_t}{X} \right) + \log \mathsf{u}_t \tag{8}$$

where $\varepsilon_{\pi X} = \frac{(1-\theta_\pi)(1-\beta g_C \theta_\pi)}{\theta_\pi (1+\beta g_C \iota_\pi)}$ denotes the elasticity of inflation to the markup and where, as in Smets and Wouters (2003), we allow for cost-push shocks that affect inflation independently from fluctuations in the real marginal cost. These shocks are assumed to be *iid* with variance σ_u^2.

To complete the model, we assume that the central bank runs monetary policy according to a standard Taylor rule that responds to inflation and GDP growth:

$$R_t = (R_{t-1})^{r_R} \left(\pi_t^{r_\pi} \left(\frac{GDP_t}{g_C GDP_{t-1}} \right)^{r_Y} \overline{rr} \right)^{1-r_R} \mathsf{e}_{Rt}. \tag{9}$$

where $\overline{rr}$ is the target, steady state real interest rate (which we assume to be equal to the patient households discount rate), and GDP sums all the components of aggregate demand, expressed in units of the consumption good.[11] Note that, around the balanced growth path, the real price of housing changes in response to preference, monetary and technology shocks. Following Davis and Heathcote (2005), our measure of real GDP uses steady state house prices, so that short-run changes in real house prices do not affect GDP.

The terms e_{Rt} captures a zero-mean monetary policy shock, with variance σ_R^2.

[11] Our operational definition of GDP growth sums up the growth rates of real consumption, real residential investment and real business fixed investment by their steady state nominal shares. That is, $GDP_t = C_t + IK_t + \overline{q} IH_t$, where $\overline{q}$ denotes real housing prices along the balanced growth path. We exclude imputed rents from the GDP that enters the model Taylor rule above. In our model, imputed rents are simply $v_t h_t + v_t' h_t'$, where v_t and v_t' are the relative price of housing services, obtained dividing the marginal utility of housing by the marginal utility of consumption. We do so because our model obviously implies a tight mapping because house prices and rents, something that does not seem to hold in the data. Including rents in model definition of GDP would be too close to including house prices themselves in a Taylor rule, and would imply a mechanical mapping between house prices and consumption of housing services.

2.4. Market clearing

We assume that total land is fixed, and normalize its total supply to unity. The three market clearing conditions are:

$$C_t + IK_{ct}/\mathsf{A}_{kt} + IK_{ht} = Y_t - \phi_t \tag{10}$$

$$h_t + h'_t - (1-\delta_h)\left(h_{t-1} + h'_{t-1}\right) = IH_t \tag{11}$$

$$b_t + b'_t = 0 \tag{12}$$

where $C_t = c_t + c'_t$ is aggregate consumption, and $IK_{ct} = k_{ct} - (1-\delta_k) k_{ct-1}$ and $IK_{ht} = k_{ht} - (1-\delta_k) k_{ht-1}$ are the two components of total, nonresidential business fixed investment, expressed in real units.

2.5. Trends and balanced growth

We assume deterministic, heterogeneous trends in productivity in the consumption sector, the business fixed investment sector, and the housing sector. To this purpose, we let the processes for sector-specific productivity to follow:

$$\begin{aligned}
\ln \mathsf{A}_{ct} &= t \ln(1+\gamma_{AC}) + \ln A_{ct}, \qquad \ln A_{ct} = \rho_{AC} \ln Z_{ct-1} + \varepsilon_{ct} \\
\ln \mathsf{A}_{ht} &= t \ln(1+\gamma_{AH}) + \ln A_{ht}, \qquad \ln A_{ht} = \rho_{AH} \ln Z_{ht-1} + \varepsilon_{ht} \\
\ln \mathsf{A}_{kt} &= t \ln(1+\gamma_{AK}) + \ln A_{kt}, \qquad \ln A_{kt} = \rho_{AK} \ln Z_{kt-1} + \varepsilon_{kt}
\end{aligned}$$

where the innovations $(\varepsilon_{ct}, \varepsilon_{ht}, \varepsilon_{kt})$ are serially uncorrelated with mean zero and standard deviations $(\sigma_{AC}, \sigma_{AH}, \sigma_{AK})$, and the terms $(\gamma_{AC}, \gamma_{AH}, \gamma_{AK})$ denote the net growth rates of productivity in each sector. Given this setup, a balanced growth path exists since preferences and all production functions have a Cobb-Douglas form. In the balanced growth path, the gross growth rates of the real variables will be:[12]

$$\begin{aligned}
g_C &= g_{IK_h} = g_{q \times IH} = 1 + \gamma_{AC} + \frac{\mu_c}{1-\mu_c}\gamma_{AK} \\
g_{IK_c} &= 1 + \gamma_{AC} + \frac{1}{1-\mu_c}\gamma_{AK} \\
g_{IH} &= 1 + (1-\mu_l)\gamma_{AC} + \frac{\mu_c \mu_h}{1-\mu_c}\gamma_{AK} + (1-\mu_h-\mu_l)\gamma_{AH} \\
g_q &= 1 + \mu_l \gamma_{AC} + \frac{\mu_c(1-\mu_h)}{1-\mu_c}\gamma_{AK} - (1-\mu_h-\mu_l)\gamma_{AH}.
\end{aligned}$$

[12] Given our assumptions about investment specific technological change in the nonresidential investment sector, actual investment will include two components - k_c and k_h - that grow at different rates (in real terms) along the balanced growth path. In the data, we only have a chain-weighted series (non-residential fixed investment) for the aggregate of these two series, since sectoral data on capital held by the construction sector are available only at annual frequency and are not reported in the National Income and Product Accounts. Because both in our model and in the data the capital held by the construction sector is a very small fraction of non-residential capital (we target a ratio of $k_h/(k_c+k_h)$ around 0.05), we assume that in the data total investment grows at the same rate as investment in the consumption good sector in our model.

We note some interesting properties of these growth rates. First, the trend growth rates of IK_{ht}, IK_{ct}/A_{kt} and $q_t IH_t$ are all equal to g_C, the trend growth rate of real consumption: this growth rate is a weighted growth rate of neutral and investment-specific technological progress. Second, the growth rate of business investment is the same as the growth as consumption, when investment is expressed in units of consumption; in real terms, instead, business investment grows faster than consumption, as long as $\gamma_{AK} > 0$ and $\mu_c < 1$. Third, the trend growth rate in real house prices exactly offset differences in the productivity growth between the consumption and the housing sector: these differences are due to the presence of land in the production function for homes, to the heterogeneous rates of investment-specific technological change, to the sector specific technological progress in the housing sector.

2.6. Discussion of the model setup

Our modeling choices reflect the desire to strike a balance between a rich and realistic model, and the need to keep the structure simple: simplicity allows us to get a better sense for the key mechanisms at work in the model, considerably speeds up computing time, and makes the basic logic behind our model more transparent. We briefly explain below some of our modeling choices, and why we adopted them.

1. Our first assumption is that consumption and nonresidential investment are produced using the same factor mix, whereas a different technology combines capital produced in the consumption sector with labor and land to produce new homes.[13] We find this approach a somewhat natural way to proceed, since it allows for different factor intensities in the two sectors, for different rates of technological progress, for different equilibrium prices of consumption and housing.

2. We do not assume adjustment costs for housing on the demand side. Obviously, housing investment is lumpy at the individual level, and home purchases are subject to obvious and readily identifiable transaction costs. Yet most of these costs do not seem to be "quadratic" in nature. Transaction costs in the housing market involve a fixed fee and a cost that is proportional to the value of the house.

3. We assume habits in consumption only. We have experimented with habits in housing and leisure, and found no substantial differences in our results.

4. We assume that hours of the two households enter the production functions in a Cobb-Douglas function. The advantage of this formulation is that the "weight" of the constrained households in the production function has the natural interpretation of the share of labor income accruing

[13] At the cost of heavier notation, one could easily reinterpret our setup as a three sector model. We prefer not to do so, since, using the same logic, one could reinterpret even that standard one-sector neoclassical growth model as a two sector model.

to constrained agents. Were the production functions linear in the hours of the two types, there would be additional feed-back effects between hours and consumption stemming from the presence of borrowing constraints.[14] We have experimented with such formulation, and the quantitative differences between the framework we adopt and the linear-labor framework were very small.

5. We assume staggered price setting, but allow wages to be perfectly flexible. In Section 6, we sketch an extension of our model with sticky wages. Our findings suggest that sticky wages do not alter the main message of the paper, but they are a successful extension in two dimensions: first, they reduce the amount of nominal price rigidity that is needed to fit the data; second, they can account for a stronger negative response of residential investment to a monetary contraction, along the lines suggested by Barsky, House and Kimball (2006) and Carlstrom and Fuerst (2006).

3. Estimation of the model

Since a closed form solution is not possible, we study the behavior of the economy by considering a loglinear approximation to the model equations in the neighborhood of the steady state of the detrended variables. In steady state the shocks are set to their mean values, price inflation is set to zero, the risk-free interest rate is equal to the patient agents' discount rate. The steady state is solved in closed-form.

3.1. The Bayesian estimation

The estimation procedure consists of various steps: the transformation of the data into a form suitable for the computation of the likelihood function using the stationary state-space representation of the model; the choice of appropriate prior distributions; the estimation of the posterior distribution with Monte Carlo methods. These steps are discussed in turn in this section.

The Bayesian approach starts form the assertion that both the data Z and of the parameters Θ are random variables. Starting from their joint probability distribution $P(Z, \Theta)$ one can derive the fundamental relationship between their marginal and conditional distributions known as Bayes theorem:

$$P(\Theta|Z) \propto P(Z|\Theta) \times P(\Theta).$$

The Bayesian approach reduces to a procedure for combining the *a priori* information we have on the model, as summarized in the prior distributions for the parameters $P(\Theta)$, with the information that comes from the data, as summarized in the likelihood function for the observed

[14] When hours of the two groups independently enter the production function in a Cobb-Douglas fashion, wage shares are a constant fraction of total income for both agents. When the hours of the two groups are perfect substitutes, wages are equal within each sector, and the consumption-labor supply decision of one group affects the wage income of the other group too.

time series $P(Z|\Theta)$. The resulting posterior density of the parameters $P(\Theta|Z)$ can then be used to draw statistical inference either on the parameters themselves or on any function of them or of the original data.

3.2. The data

Estimation is based on eight quarterly macroeconomic variables over the period 1965Q1-2005Q4: real consumption, the inflation rate, real residential investment, real business investment, real house prices, the 3-month short-term nominal interest rate and total hours worked in the construction and in the non-construction sectors. Our series are plotted in Figure 1 and described more in detail in Appendix A. Our choice of the initial period is dictated by the availability of the house price series, which starts in 1965.[15]

The model has implications for the deviations from steady state growth path of all these variables: in equilibrium, the transformed variables $\widehat{C}_t = C_t/g_C^t$, $\widehat{IK}_t = IK_t/g_{IK}^t$, $\widehat{IH}_t = IH_t/g_{IH}^t$, $\widehat{q}_t = q_t/g_q^t$ all remain stationary.[16] In addition, given the King-Plosser-Rebelo form of the utility function, total hours in the two sectors N_{ct} and N_{ht}[17] remain stationary, as do inflation π_t and the nominal interest rate R_t.

We linearize the set of equations that describe the equilibrium of our model around the balanced growth path. For given parameter values, the solution to our model takes the form of a state-space econometric model, thus allowing to compute the likelihood function.

3.3. Calibrated parameters and Prior Distributions

Calibration. The parameters we calibrate include the discount factors: β, β'; the weight on housing relative to consumption in the utility function j; the technology parameters: $\mu_c, \mu_h, \mu_l, \delta_h, \delta_{kc}, \delta_{kh}$; the steady state gross markup X. We pick values for these parameters on the basis of the data sample means and other studies because they contain relatively more information on the first moments

[15] For house prices, we used the quality-adjusted Census Bureau house price index, that refers to the price index of new one-family houses sold including value of lot. An often used house price series – based on repeat sales – is the Freddie Mac/OFHEO Conventional Mortgage House Price Index (CMHPI, dating back to 1970). At business cycle frequencies, this series moves together with the Census series (for instance, the correlation between year-on-year real growth rates of the two series is 71 percent). Over the 1970-2005 period, the CHMPI has a stronger upward trend: the Census series grows in real terms by an average of 1.7 percent per year, the CHMPI series by 2.3 percent. Because it is based on repeat sales, the CMHPI is perhaps a better measure of house price appreciation at short-run frequencies; however, several authors have argued that the CHMPI series is biased upward (between 0.1 and 0.6 percent per year) because homes that change hands more frequently tend to have greater price appreciation (see Gallin, 2004, for a discussion). Because it starts earlier, we prefer to use the Census series.

[16] In steady state, asset (debt) holdings, wages and consumption of each group will all grow at the same rate as aggregate consumption. We scale each variable by its trend growth rate before linearize our model around the steady state.

[17] Consistently with the aggregator we use in the production function, we define our indexes of total hours as $N_{ct} = n_{ct}^{\alpha}(n'_{ct})^{1-\alpha}$ and $N_{ht} = n_{ht}^{\alpha}(n'_{ht})^{1-\alpha}$.

of the data.[18]

We set $\beta = 0.992$, implying a steady state real interest rate of 3 percent on an annual basis. We pick a value for the discount factor of the impatient households (β') equal to 0.97; this value has no big effect on the dynamics of the model, but guarantees an impatience motive large enough that the borrowing constraint is always binding: see Iacoviello (2005) for a discussion. We fix $X = 1.15$, implying a steady state markup of 15% in the consumption-good sector.

The depreciation rates for housing, capital in the consumption good sector and capital in the construction sector are set equal respectively to $\delta_h = 0.01$, $\delta_{kc} = 0.025$ and $\delta_{kh} = 0.03$. The first number pins down the ratio of residential investment to GDP at around 5 percent, as in the data. The other two numbers - together with the capital shares in the production function - imply a ratio of business fixed investment to GDP around 25 percent. We pick a slightly higher value for the depreciation rate of construction capital on the basis of BLS data on service lives of various capital inputs,[19] that indicate that construction machinery has a lower service life than other types of nonresidential equipment.

For the capital share in the production function of goods, we choose a standard value of $\mu_c = 0.35$. In the production function for new homes, we choose a capital share of $\mu_h = 0.15$ and a land share of $\mu_l = 0.10$. The calibration of the last two numbers follows Davis and Heathcote (2005: Table 3 and footnote 19), and implies that the construction sector is relatively more labor intensive. Finally, the weight on housing in the utility function is set at $j = 0.12$. Together with the other technology parameters, these choices imply that the ratio of total net wealth (the sum of fixed capital, land and housing wealth) to total, annualized GDP is around 3, whereas the ratio of housing wealth to GDP is around 1.3.[20]

Priors Our priors are in the last three columns of Table 1. We choose a rather loose prior for the standard errors of the innovations. For the persistence of the AR(1) process, we choose a beta-distribution with a prior mean of 0.8 and standard deviation of 0.1. We set the prior mean of the habit parameters in consumption (ε_c and ε'_c) at 0.5 (with a standard error of 0.075). For the

[18] Some of the parameters that we estimate (namely, labor income share of unconstrained agents α, and the loan-to-value ratio m) also affect some of the steady state ratios that the calibration aims at pinning down (this happens because in steady state the two groups have different marginal propensities to consume and to save). In preliminary estimation attempts, we fine-tuned the calibrated parameters so ensure that our target ratios were roughly as desired given the posterior distribution of the estimated parameters.

[19] See http://www.bls.gov/mfp/mprcaptl.pdf (Table 1, service lives of private nonresidential equipment).

[20] That is, steady state GDP is defined as

$$GDP = \underbrace{c + c'}_{\text{Consumption.}} + \underbrace{IK}_{\text{non-residential fixed investment}} + \underbrace{qIH}_{\text{residential investment}},$$

whereas steady state net wealth is defined

$$NW = \underbrace{k_h}_{\text{Private } k \text{ in construction sector}} + \underbrace{k_c}_{\text{Other private } k} + \underbrace{q\left(h + h'\right)}_{\text{Residential housing stock}}.$$

monetary policy specification, we base our priors on a standard Taylor rule responding (gradually) to inflation only, so that the prior means of r_R, r_π and r_Y are respectively 0.75, 1.5 and 0. We set a prior on the capital adjustment costs around 10 with a standard error of 2.5.[21]

Moving to the parameters describing the disutility of working, we center the elasticity of the hours aggregator for each agent around 2 (that is, the prior mean for η and η' is around 0.5). We select values for ν and ν', the parameters describing the inverse elasticity of substitution across hours in the two sectors, around -2: high values for these numbers in absolute terms are needed (and are preferred by the model, as we will see) to generate positive comovement in hours across the two sectors.[22]

We select the prior mean of the Calvo parameter θ_π to be around 0.75, with a standard deviation of 0.05. The prior for the indexation parameter ι_π is loosely centered around 0.5.

Finally, our prior mean for the loan to value ratio is set around 0.8, with a small standard error, on the assumption that this number is readily identifiable from common practice in the mortgage market. We set the prior mean for the labor income share of unconstrained agents to be 0.65, with a standard error of 0.05. This prior is between the range of estimates in the literature: for instance, using aggregate data, Campbell and Mankiw (1989) estimate a fraction of rule-of-thumb/constrained consumers around 40 percent. Using the 1983 Survey of Consumer Finances, Jappelli (1990) estimates 20 percent of the population to be liquidity constrained.

4. Results

4.1. Posterior Distributions

We estimate 32 parameters. Of these, 14 pertain to the standard deviation and the autocorrelation of the shocks (we assume eight shocks, but do not allow for autocorrelation in the monetary shock and the inflation shock). Three parameters govern the rate of technological progress (for consumption goods, capital and housing), two measure capital adjustment costs, two measure the degree of habit formation, four pertain to the labor supply schedule (labor supply elasticity and elasticity of substitution across sectors), two to the Phillips curve (price rigidity and inertia), and three to the Taylor rule coefficients. The remaining two parameters, α and m, measure respectively the labor income share of unconstrained households and the average loan-to-value ratio for the credit-constrained agents.

We report the estimated posterior mean, median and confidence intervals for our estimated parameters in Table 1.

Our estimated results can be summarized as follows. The estimate of the Calvo parameter ($\theta_\pi = 0.92$) implies that prices are reoptimized very infrequently, once every 3 years. However,

[21] Given our capital adjustment cost specification, the implied elasticity of investment to its shadow value is given by $1/\phi\delta$. Our prior corresponds to an elasticity of investment to its shadow price of around 4, a reasonable value.

[22] Using a similar functional form, and using a reduced form approach, Horvath (2000) estimates a value of ν equal to -1.

a large fraction ($\iota_\pi = 0.85$ at the median estimate) of the retailers who do not reoptimize still index prices to the previous period inflation rate.[23] We interpret these numbers as evidence that prices are not very sensitive to the marginal cost measure implied by our model. As is well known, the parameter θ_π only enters the coefficient on the markup in the Phillips curve equation: to the extent that inflation is not very sensitive to marginal costs, the estimate of θ_π tends towards one. Some real rigidities that we do not model (fixed costs of production, or firm-specific capital) would generate the same reduced form for our model and would show up as a multiple (larger than one) of θ_π in the Phillips curve, thus reducing the implied degree of price rigidity to much lower values.[24]

Another feature of our estimated model is that capital in the construction sector is less costly to adjust than capital in the consumption sector ($\phi_{kc} > \phi_{kh}$). Together with the high volatility of the Solow residual in the construction sector, it generates high volatility of residential investment. Both agents exhibit moderate-to-high degree of habit formation in consumption, relatively high labor supply elasticities, and relatively little preference for mobility across sectors, as shown by the somewhat large negative values of ν and ν'.

We find a faster rate of technological progress in the business fixed investment sector, following by the consumption good sector, and by the housing sector. At the posterior mean, the estimates imply, in particular, that the long-run annualized growth rates of real per worker consumption, real per worker housing investment and real house prices are respectively 1.90 percent, 0.55 percent and 1.35 percent. That is, the secular rise in real house prices seen in the data reflects, in our model, faster technological progress in the non-housing sector. The slow growth rate of TFP in the construction sector is perhaps not surprising nor new, although it has not been cited often as one of the explanations for the increase in house prices seen in the data: Corrado et al. (2006) construct measures of TFP growth for the period 1987-2004 at sectoral level for the US economy and they find that, for the construction sector, measured productivity change is negative, and increases in the contribution of labor and purchased inputs more than account for the real output growth of the sector. Stiroh (2002) computes measures of productivity growth across industries and finds negative labor productivity growth in the construction sector: in particular, he finds that the productivity gap between housing and other sector was smallest in the period 1987-1995, when house prices dropped substantially in real terms.

Our key parameters of interest relate to the loan-to-value ratio and to the fraction of credit constrained agents. The estimated value of m essentially lines up with its prior. As for α, our model implies a share of labor income of credit constrained agents around 21%. This fraction is enough to generate a positive elasticity of consumption to a housing shock, something that we discuss more in detail in the next section.

Finally, all shocks are estimated to be quite persistent.

[23] However, a large fraction ($\iota_\pi = 0.705$) of the retailers who do not reoptimize still index prices to the previous period inflation rate.

[24] See for instance Levin, Lopez-Salido and Yun (2006).

4.2. Impulse Responses

In this section, we discuss the main workings of our model by presenting the impulse responses at the estimated posterior median (alongside 5 and 95 percent confidence bounds). The effects of most shocks are familiar.

Of particular interest are the effects of the housing preference shock (a persistent increase in the marginal utility of housing), shown in Figure 3. By causing an increase in house prices, the disturbance produces two effects. On the one hand, it raises the returns to investing in the construction sector, thus causing residential investment to rise. On the other, it increases the collateral capacity of constrained agents, thus causing their consumption to increase. Because they have a high propensity to consume at the margin, the effects on aggregate consumption are positive, even if consumption of the lenders falls (as shown in the bottom panel of the figure). The size of the effect depends on α, the labor income share of unconstrained people. Intuitively, when α is high, few agents are credit constrained, and the housing preference shock causes a shift of resources from the consumption to the construction sector, thus causing a larger boom in housing investment. When α is low, many agents are credit constrained, and a housing boom causes resources to be shifted to these agents (and diverted from firms), with a larger impact on aggregate consumption rises. To illustrate the mechanism, Figure 4 plots the short-run elasticities[25] of the three components of aggregate demand (C, IH and IK) to house prices, for different values of α. Our mean estimate of α (around 21 percent) percent implies a medium-run elasticity of consumption to housing around 0.05, and an elasticity of investment to house price shocks around 0.3. It is this mechanism that allows us to identify the parameter α in estimation, since the responses to other shocks are less sensitive to alternative values of α.[26] Hence, the presence of credit constrained households shifts the action from investment to consumption.

Figure 5 displays the model responses to an adverse monetary policy shock. Perhaps the most interesting aspect is that the response of residential investment, while negative, is smaller than the response of business fixed investment, and of the same order of magnitude as the response of consumption. That *flexible price* durable goods would tend to move countercyclically in response to monetary shocks has been stressed by Barsky, House and Kimball (2006), Carlstrom and Fuerst (2006) and Monacelli (2006).[27] The mechanism at work in our paper that generates comovement across sectors is the low elasticity of substitution across hours in the two sectors. However, quanti-

[25] These responses are computed calculating the average deviation from the baseline of each series for the first 4 quarters after a shock.

[26] In Figure 16 we compare the responses of the economy for two somewhat polar values of α, 0.5 (so that 50% of labor income accrues to constrained agents) and 1 (so that there are no credit constraints). Besides generating a positive wealth effect on consumption from house price changes, credit constraints are also capable of avoiding a positive response of housing investment to an adverse monetary policy shock. See also Monacelli (2006) for further discussion of these issues.

[27] This result occurs because the reduction in demand in the consumption good sector leads to a decline in the production cost of housing goods, and thus to an expansion in that sector.

tatively the response of residential investment to a monetary shock, while negative, is smaller than what is typically found in VAR studies (see for instance Erceg and Levin, 2005).

We plot the impulse responses to the other shocks in Figures 6 to 11. An aggregate productivity shock (Figure 6) leads to an increase in investment and consumption, a drop in inflation, and an increase in house prices. Employment in both sectors slightly drops. A housing sector specific productivity shock (Figure 7) leads to a strong increase in residential investment, a drop in house prices, and, with some delay, to an increase in fixed investment and consumption. An adverse cost-push shock (Figure 8) leads to an increase in inflation and nominal rates, and a decline in economic activity. A positive investment technology shock (Figure 9) generates a sharp increase in fixed investment, and delayed positive effects on the other components of aggregate demand.[28] A positive preference shock (Figure 10) generates an increase in consumption, and a decline in investment and house prices. Finally, a negative labor supply shock (Figure 11) leads to a decline in hours, consumption, investment and house prices.

4.3. Variance Decompositions and other moments

Table 2 compares the business cycle properties of our model with those from the data. It shows that our model accounts well for most moments of the actual time-series.

In Table 3 we present the results from the variance decomposition exercise. Two results immediately stand out. First, a large fraction of volatility (around 68 percent of the asymptotic variance) in residential investment is due to housing investment shocks. Second, around 66 percent of house price volatility can be accounted for by shifts in the marginal rate of substitution between housing and other goods. Figure 12 largely confirms this finding, summarizing the historical contributions of the various shocks to developments in housing prices and housing investment.

At first, this might be disappointing. We view in any case as informative that while the usual suspects (technology, money, inflation shocks) can account for a large chunk of economic fluctuations, they fall short of accounting for the observed volatility of housing prices and investment at business cycle frequencies, so that their "own" innovations, that one can think of as residuals, are forced to explain the residual variance.[29]

Why are measures of technology shocks in the construction sector considerably more volatile than in the other sector?[30] Here, we offer some speculative comments. First, the low volatility of the Solow residual in the other sector might reflect aggregation bias. Second, by its own nature, the

[28] Unlike the aggregate productivity shock, this shock leads to an increase in hours. This is roughly consistent with the VAR evidence in Fisher (2006), although the comparison is hindered by the fact that he assumes unit-root, rather than trend-stationary, shocks.

[29] To a first approximation, these results also hold in a simple VAR estimated on the actual time-series used on estimation: even in this setup, most of the variance of house prices and housing investment can be explained by own innovations.

[30] Davis and Heathcote (2005) also uncover lack of productivity growth and high volatility of the detrended Solow residual in the construction sector.

construction sector is more exposed to seasonal cycles, for instance due to the effects of weather.

There are however two important lessons that we learn from the exercise: even with suitably chosen frictions, aggregate technology shocks and monetary shocks cannot fully account for the observed volatility in housing prices and housing investment. However, we find it important that heterogeneous trend in technology can simultaneously account for trend both in real housing prices and real housing investment. Second, because a large part of house prices fluctuations at medium to high frequency can, to some extent, be viewed as exogenous, the estimated model offers us the possibility to ask the counterfactual question: how big has been the contribution of the *housing demand boom* to the recent US business cycle? We investigate this question in the next section.

5. Applications

5.1. The contribution of housing prices to the turn-of-the-century recovery

> Greenspan "Nonetheless, it is difficult to dismiss the conclusion that a significant amount of consumption is driven by capital gains on some combination of both stocks and residences, with the latter being financed predominantly by home equity extraction" (Alan Greenspan)[31]

Several commentators, policymakers and central bankers have remarked how the housing boom of the turn of the century has stimulated consumption through home equity withdrawal on the one hand, and employment and production in the construction industry on the other. In this subsection, we look closely at the recent housing boom, and quantify its extent on the one hand, and its feedback on aggregate demand on the other. We do so by comparing the actual data with the data that obtain shutting off the housing preference shock, beginning in 2002Q1: this is the period when the model identifies the beginning of the housing boom, through a series of above average realizations of ε_{jt}, the i.i.d. component of the autoregressive housing preference shock.

A comparison of the actual with the counterfactual data (shown in Figure 13) allows quantifying how the housing boom has contributed to strong consumption and strong residential investment throughout the period. Without the housing boom, real consumption would have been roughly half a percentage point lower, whereas real investment would have been about four percent lower![32] Clearly, the sheer size of the recent housing boom has had a non-negligible impact on aggregate demand.

[31] http://www.federalreserve.gov/boardDocs/Speeches/2005/200509262/default.htm

[32] Because we plot the real variables in log deviations from trend, the figures give the cumulative impact on consumption and residential investment throughout the period in exam. Because, as shown by the Figure, these effects have been spread out over a period of about four years, the effects of the housing boom on average annual growth in consumption and residential investment are about 0.12 percent and 1 percent respectively.

5.2. What if the Fed had been aggressive against house prices inflation?

> "Thus, at this point, a leveling out or a modest softening of housing activity seems more likely than a sharp contraction, although significant uncertainty attends the outlook for home prices and construction. In any case, the Federal Reserve will continue to monitor this sector closely." (Ben Bernanke)[33]

In Figure 14, we compare actual and counterfactual series under the assumption that the Fed directly responds to real house prices beginning in 2002Q1. That is, we simulate the model history until 2001 under the assumption that the Fed does not respond to house prices. At the onset of the identified housing boom, we assume that the Fed changes policy and responds to real house prices (with a response coefficient equal to r_π), and agents behave from then on in accordance with the Fed policy. The change is assumed to be unanticipated, permanent, fully credible, and immediately learnable by the agents. We then feed in the model the sequence of our estimated smoothed shocks, and compare the realizations of the model series with the actual data. We find that the US would have experienced high interest rates, only slightly lower house price inflation, and much lower output growth if the Fed had responded to house prices.[34]

5.3. Financing constraints and the Great Moderation

Great Moderation. To what extent might financing constraints have played a role in the Great Moderation? To address this question, we estimate the model recursively for various subsamples, starting with the period 1965Q1-1984Q4 and moving the estimation window ahead one year at the time, while keeping the size of the sample constant at 20 years. The last subsample is thus 1986Q1-2005Q4, which means that we produce 22 posterior distributions for each of our estimated parameters.[35] We find that, for large part, most of the Great Moderation seems to be accounted by reduced volatility of the underlying macroeconomic shocks.[36] Variations in most of the model structural parameters seem minor in size and temporary in nature. One interesting exception has to do with the parameters of the Taylor rule. In the later part of the sample, it appears that the policy rule has become more aggressive against inflation.

[33] http://www.federalreserve.gov/boarddocs/hh/2006/february/testimony.htm

[34] We have simulated our model shutting off monetary policy shocks from 2002Q1 on. We have found the contribution of monetary policy shocks to house prices to be minimal, consistently with the VAR evidence in DelNegro and Otrok (2005).

[35] A similar exercise in the context of a simple dynamic-new-keynesian model is also undertaken by Canova (2005).

[36] Campbell and Hercowitz (2006) address this question in detail in a one-sector model with a similar financing constraint without nominal rigidities. They find that differences in loan-to-value ratios before and after the 1980s can explain a large fraction of the Great Moderation, since large loan-to-value ratios work to reduce the labor supply response of constrained agents to productivity shocks. Their setup implicitly assumes that all workers are credit constrained (in terms of our setup, they set $\alpha = 0$, and change m across subperiods): for this reason, we regard their story plausible from a qualitative standpoint, less so from a quantitative one.

Evolution of credit constraints over time. Who are the credit constrained people? In our model, credit constrained agents happen to be constrained because they discount the future heavily, and are up against the maximum borrowing limit at the equilibrium interest rate. A natural question to ask is whether we can map the credit constrained people, that in our model we indirectly infer from the data, to something that can be observed more directly. There are reasons to believe that credit constraints apply more often to young people, who, as remarked by Tobin (1980), are "frequently young families acquiring homes and furnishings before they earn incomes to pay for them outright; given the difficulty of borrowing against future wages, they are liquidity-constrained and have a high marginal propensity to consume."

In Figure 15, we plot recursive estimates of $1-\alpha$, the labor share of constrained agents, against the 20-year moving average of the fraction of US population aged between 25 and 39. Indeed, there is a close positive correlation between the two series (around 60 percent). We view this as suggestive evidence that demographics, by affecting the fraction of agents who are credit constrained, might have interesting implications for business cycle dynamics.

6. A Sticky-Price, Sticky-Wage Economy

[VERY PRELIMINARY]

Barsky, House and Kimball (2006) and Carlstrom and Fuerst (2006) have remarked the importance of sticky wages to account for the large negative elasticity of durable consumption and residential investment following a monetary tightening. They show how models with sticky non-durable prices and flexible durable prices generate a counterfactual boom in durable expenditure after a negative monetary shock. Our estimated model avoids result this through credit constraints, a low degree of intersectoral mobility and high rigidity in the sticky price sector. Yet the response of residential investment to a monetary tightening (shown in Figure 6) is only slightly negative, and of the same order of magnitude of that of consumption.

We can adapt our model to account for wage rigidity. We follow Erceg, Henderson and Levin (2000) to allow for monopolistic competition at the wage-setters level and Calvo-style wage adjustment at level of each group of workers for each sector. The labor supply schedules now include a wage markup between the marginal benefit of working and its disutility cost. In addition, wage inflation depends on current and future expected changes in the wage markup. We estimate the model as before by adding real wages as an additional observable (nine series), and allowing for observation error in the hours in the construction sector (eight shocks plus one source of observation error). Besides the previous parameters, we now also estimate the probability of not-adjusting wages θ_w and the inertia in the wage setting behavior ι_w. We find moderate wage rigidity ($\theta_w = 0.46$); our estimate of the nominal price rigidity substantially drops (θ_π drops from 0.92 to 0.82); larger negative effects of monetary shocks on residential investment: in particular, the initial response of residential investment to a monetary shock is similar in size and shape to that of business fixed investment.

7. Related Literature

7.1. Where does our paper belong?

Our approach is related to several strands of literature.[37] In particular, it combines four main elements: (1) two sectors, one producing consumption and investment goods, the other producing new housing; (2) nominal rigidities; (3) financing frictions in the household sector; (4) a rich set of shocks, which are essential to take the model to the data.

Greenwood and Hercowitz (1991) is perhaps the most well-known paper dealing with (1) . In their setup, the "consumption" sector produces consumption goods, nonresidential capital and residential capital, whereas the housing sector uses residential capital to produce housing services. (In our formulation, the non-housing sector produces an intermediate investment good that is then combined with labor and land to produce homes). Greenwood and Hercowitz interpret the two capital stocks in the non-housing sector as nonresidential and residential capital, and calibrate their model accordingly; instead, our two types of capital k_h and k_c stand for capital in the construction sector (such as cranes, tractors and the like) and all other nonresidential capital, respectively. Unlike us, they assume reversibility between residential and business capital, which implies that the relative price of housing will always be unity. Davis and Heathcote (2003) use a multisector model with intermediate goods production in which construction, manufacturing and services are combined, in different proportions, to produce consumption, business investment, and residential structures. Residential structures are then combined with land to produce new homes. On the supply side, we follow their lead, so that our setup shares some features with theirs. Obviously, because our goal is to take the model to the data and to use it for monetary policy analysis, we allow for a rich set of intertemporal and intratemporal disturbances and stochastic shifts in productivity.

Edge, Kiley and Laforte (2005) integrate (1), (2) and (4). They distinguish between two production sectors, which (as in our paper) differ in their long-run growth rates of technological progress. They also distinguish between several categories of household expenditure, namely consumption of nondurables and services, investment in durables, and investment in residences. Bouakez, Cardia and Ruge-Murcia (2005) estimate a model with heterogenous production sectors that differ in price stickiness, capital-adjustment costs and production technology, and use output from each other as material and investment inputs following an Input-Output Matrix and Capital Flow Table that represent the U.S. economy. None of these papers deals explicitly with housing prices and housing investment, which are, instead, our main focus of analysis.[38]

Several papers have done a better job than us in developing realistic models of housing investment in models with incomplete markets and financing frictions on the household side, combining elements of (1) and (3) . Gervais (2002) and Diaz and Luengo-Prado (2005) look at the properties

[37] For obvious reasons, we refrain from offering a detailed survey of all papers that have dealt with housing and business cycle, and we refer the reader to Leung (2004) for a detailed survey.

[38] Monacelli (2006) attempts at integrating (1) , (2) and (3) in a model without capital, but he limits itself to studying how borrowing constraints and nominal debt affect the response of durables to a monetary shock.

of housing investment in a model in which housing is illiquid and can be used as collateral: however, they care about quantities not prices. Nakajima (2005) looks at the long-run implications for housing prices of earnings uncertainty: in his setup, housing prices move, but the quantity is fixed. Lustig and Van Nieuwerburgh (2005) study in detail the asset pricing implications of this class of models.[39]

7.2. What drives housing prices? Some alternative explanations

Our estimated model suggests that, at secular frequencies, residential investment and house prices can be largely accounted by slow technological progress in the housing sector. Instead, at cyclical frequencies, we find that the largest bulk of fluctuations in house prices come from shifts in the marginal utility of housing.

It is instructive to put the result into the context of the large and growing macro (non DSGE) literature which has tried to explain short and long-run fluctuations in the price of housing.

1. Martin (2006) uses a Lucas asset pricing model to quantitatively account for the secular in real house prices, the path of real interest rates, and the timing of low-frequency fluctuations in real house prices over the period 1963-2003. The model predicts that the primary force underlying the evolution of real house prices is the systematic and predictable changes in the working age population driven by the baby boom. In his basic setup, the housing stock is fixed, and changes in the size of the working age population determine the labor input into the production function.

2. Some studies have looked at the link between inflation and asset prices. Brunnermeier and Parker (2006) show that a reduction in inflation can fuel run-ups in housing prices if people suffer from money illusion. When individuals have to decide whether to rent or buy, money illusion from lower inflation tilts preferences from renting towards owning, thus raising house prices when inflation is low, and depressing them when inflation is low. Their mechanism is well suited to explain the recent housing boom, but cannot explain why house prices went up during the high-inflationary episodes of the 1980s. Piazzesi and Schneider (2006a) build an OLG model to show that the Great Inflation led to a portfolio shift by making housing more attractive than equity, thus fueling the housing boom of the 1980s. Their mechanism is well suited to explain the housing boom of the 1980s, but cannot explain why house prices have gone up at the turn of the century. The same authors (Piazzesi and Schneider, 2006b)

[39] Topel and Rosen (1988) build a prototype model of residential investment without nominal rigidities and credit market frictions. In their setup, housing demand is infinitely elastic at the market interest rate, and the housing supply is curve is upward sloping, with different short and long run price elasticities. Depending on the specifications, they find a short-run supply elasticity of housing investment around unity: this value is three times larger than our estimate of the response of housing investment to a real house price shock. We feel that some form of mispecification in their estimated equation might drive the difference between our and their results. See Davis and Heathcote (2005) for a similar point.

construct an alternative model in which agents who suffer from inflation illusion interact with "smart" agents in markets for nominal credit instruments: they show that, under this assumption, nominal interest rates move with smart agents' inflation expectations, and housing booms occur whenever these expectations are either especially high or low. Their model, however, is very stylized, and it remains an open question whether it can account not only qualitatively but also quantitatively for the patterns observed in the data.

3. Glaeser, Gyourko, and Saks (2005) cite regulatory obstacles, such as stiffer zoning laws and the ability of existing owners to prevent new construction, as a primary reason why housing prices have risen so much since the 1970s.

These explanations are intriguing, but disagreements among economists clearly shows how any one-size-fits-all explanation of housing boom and busts is hard to test against competing hypotheses, and cannot offer a satisfactory account of trend and cyclical movements at the same time. We view our structural approach, with multiple shocks competing with each other to explain different properties of various macroeconomic time-series including housing prices and housing investment, as complementary to this studies and perhaps more useful if one wants to do policy or counterfactual analysis.[40] Of course, it is possible that our estimated shocks (which mechanically account for the endogenous dynamics of all our time series) might be given a more structural interpretation in light of the explanations surveyed in this section.

8. Conclusions

In this paper, we have estimated a dynamic stochastic general equilibrium model of the housing market and the business cycle. From the methodological point of view, our analysis has proceeded in the spirit of Smets and Wouters (2003), by including a relatively large range of shocks and by using Bayesian methods for model estimation and for evaluation of model fit.

At secular frequencies, we find that the dynamics of residential investment and house prices can be largely accounted by slow technological progress in the housing sector. Instead, at cyclical frequencies, we find that shifts in the marginal utility of housing are the main driver of house price fluctuations, and sector-specific technology shocks account for the high volatility of residential investment. To some extent, this means that we can treat variations in house prices as somewhat exogenous to the rest of the economy, study their feedback on consumption and investment and prices, and look at their implications for monetary policy. Large fluctuations in house prices, we find, can have a nonnegligible impact on aggregate demand.

[40] Fisher and Quayyum (2006) use a structural VAR approach to explain the dynamics of residential investment in response to aggregate TFP shocks, monetary shocks and investment-specific shocks. They conclude that high residential investment has been the result of wealth accumulation from previously high rates of technological progress.

References

[1] Barsky, Robert, Christopher House and Miles Kimball (2006), "Sticky Price Models and Durable Goods," American Economic Review, forthcoming.

[2] Bouakez, Hafedh, Emanuela Cardia, and Francisco Ruge-Murcia (2005), "The Transmission of Monetary Policy in a Multi-Sector Economy," mimeo.

[3] Brunnermeier, Markus, and Christian Juilliard, (2006), "Money Illusion and Housing Frenzies," mimeo.

[4] Carlstrom, Charles, and Timothy Fuerst (2006), "Co-Movement in Sticky Price Models with Durable Goods", mimeo

[5] Campbell, Jeffrey, and Zvi Hercowitz (2006), "The Role of Collateralized Household Debt in Macroeconomic Stabilization," mimeo.

[6] Campbell, John Y. and Mankiw Gregory N. (1989), "Consumption, Income and Interest Rates: Reinterpreting the Time Series Evidence," in Olivier J. Blanchard and Stanley Fisher eds., NBER Macroeconomics Annual 1989, Cambridge, MIT Press, 185-216.

[7] Canova, Fabio (2005), "Monetary Policy and the Evolution of the US Economy," mimeo

[8] Corrado, Carol, Paul Lengermann, Eric Bartelsman, and J. Joseph Beaulieu (2006). "Modeling Aggregate Productivity at a Disaggregate Level: New Results for U.S. Sectors and Industries", mimeo.

[9] Davis, Morris A., and Jonathan Heathcote (2005), "Housing And The Business Cycle," International Economic Review, 46, 3, 751-784.

[10] Del Negro, Marco, and Christopher Otrok (2005), "Monetary Policy and the House Price Boom across U.S. States", mimeo.

[11] Edge, Rochelle, Michael T. Kiley, and J.P.Laforte (2005), "An Estimated DSGE Model of the US Economy with an Application to Natural Rate Measures," working paper, Board of Governors of the Federal Reserve.

[12] Erceg, Christopher, Dale Henderson, and Andrew Levin (2000). "Optimal Monetary Policy with Staggered Wage and Price Contracts," Journal of Monetary Economics, 46 (March), pp. 281-313.

[13] Erceg, Chris, and Andrew Levin (2005), "Optimal Monetary Policy with Durable Consumption Goods," Journal of Monetary Economics, forthcoming

[14] Fisher, Jonas (2006), " The Dynamic Effects of Neutral and Investment-Specific Technology Shocks", Journal of Political Economy, June, 413-451.

[15] Fisher, Jonas, and Saad Quayyum (2006), "The Great Turn-of-the-Century Housing Boom", Chicago Fed Economic Perspectives.

[16] Gallin, Joshua (2004), "The Long-Run Relationship between House Prices and Rents," Finance and Economics Discussion Series, 2004-50, September.

[17] Gervais, Martin (2002), "Housing Taxation and Capital Accumulation," Journal of Monetary Economics, 49, 7, 1461–1489.

[18] Glaeser, Edward L., Joseph Gyourko, and Raven Saks, (2005), "Why Have Housing Prices Gone Up?," NBER Working Paper 11129.

[19] Greenwood, Jeremy, and Zvi Hercowitz (1991), "The Allocation of Capital and Time over the Business Cycle," Journal of Political Economy, 99, 6, 1188-214.

[20] Greenwood, Jeremy, Zvi Hercowitz, and Per Krusell (2000),. "The Role of Investment-Specific Technological Change in the Business Cycle." European Economic Review, 44, (January), 91–115.

[21] Horvath, Michael, (2000), "Sectoral Shocks and Aggregate Fluctuations," Journal of Monetary Economics, 45, 69-106

[22] Iacoviello, Matteo (2005), "House Prices, Borrowing Constraints and Monetary Policy in the Business Cycle", American Economic Review, 95, 3, 739-764.

[23] Jappelli, Tullio (1990), "Who Is Credit Constrained in the U.S. Economy?," Quarterly Journal of Economics, 105, 219-234.

[24] Leung, Charles (2004), "Macroeconomics and housing: a review of the literature," Journal of Housing Economics, 13, 4, 249-267.

[25] Levin, Andrew, David Lopez-Salido, and Tack Yun (2006), "Strategic Complementarities and Optimal Monetary Policy," mimeo.

[26] Luengo-Prado, Maria, and Antonia Diaz (2005), "Precautionary Saving and Wealth Distribution with Durable Goods," mimeo.

[27] Lustig, Hanno, and Stijn van Nieuwerburgh (2005), "Housing Collateral, Consumption Insurance and Risk Premia: an Empirical Perspective," Journal of Finance, 60, 3, 1167-1219.

[28] Martin, Robert, (2006), "The Baby Boom: Predictability in House Prices and Interest Rates," mimeo.

[29] Monacelli, Tommaso (2006), "New Keynesian Models, Durable Goods, and Borrowing Constraints," mimeo.

[30] Nakajima, Makoto (2005), "Rising Earnings Instability, Portfolio Choice, and Housing Prices," mimeo.

[31] Piazzesi, Monika, and Martin Schneider (2006a), "Inflation and the Price of Real Assets," mimeo.

[32] Piazzesi, Monika, and Martin Schneider (2006b), "Inflation Illusion, Credit, and Asset Prices," forthcoming in John Y. Campbell (ed.) "Asset Prices and Monetary Policy".

[33] Smets, Frank, and Rafael Wouters (2003), "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," Journal of the European Economic Association, 1(5), 1123-1175.

[34] Stiroh, Kevin (2002), "Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say?," American Economic Review, December.

[35] Tobin, James (1980), "Asset Accumulation and Economic Activity: Reflections on Contemporary Macroeconomic Theory".

[36] Woodford, Michael (2003). Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton, N.J.: Princeton University Press.

Appendix A. Data and sources

Aggregate Consumption (C): Real Personal Consumption Expenditure (seasonally adjusted, Billions of chained (2000) dollars, Table 1.1.5), divided the Civilian Non-institutional Population over 16 (CNP16OV). Source: Bureau of Economic Analysis.

Business Fixed Investment (IK): Real Private Non Residential Fixed Investment (seasonally adjusted, Billions of chained (2000) dollars, Table 1.1.6.), divided by CNP16OV. Source: Bureau of Economic Analysis.

Residential Investment (IH): Real Private Residential Fixed Investment (seasonally adjusted, Billions of chained (2000) dollars, Table 1.1.6.), divided by CNP16OV. Source: Bureau of Economic Analysis.

Inflation (π): Quarter on quarter log differences in the Implicit Price Deflator for the Nonfarm Business Sector.

Nominal Short-Term Interest Rate (R): Nominal 3-Month Treasury Bill rate (Secondary Market Rate), expressed in quarterly units. Series ID: H15/H15/RIFSGFSM03_NM. Source: Board of Governors of the Federal Reserve System.

Real House prices (q): Census Bureau house price index (new one-family houses sold including value of lot) deflated with the Implicit Price Deflator for the Nonfarm Business Sector. Source: Census Bureau, http://www.census.gov/const/price_sold_cust.xls. A description of this price index is at http://www.census.gov/const/www/descpi_sold.pdf

Hours in Consumption-Good Sector (N_c): Total Nonfarm Payrolls (Series ID: PAYEMS) less All Employees (Series ID: USCONS) in the Construction Sector, times Average weekly hours of production workers (series ID: CES0500000005), divided by CNP16OV. Source: U.S. Department of Labor: Bureau of Labor Statistics.

Hours in Housing Sector (N_h): All employees in the construction sector (Series ID: USCONS. Source: U.S. Department of Labor: Bureau of Labor Statistics) times Average weekly hours of construction workers (series ID: CES2000000005), divided by CNP16OV.

Appendix B. Details on the model

We summarize here the complete set of non-linear equations describing the equilibrium of our model. Let u_c denote the marginal utility of consumption, u_{nc} (u_{nh}) the marginal disutility of working in the goods (housing) sector, u_{ht} the marginal utility of housing.

The first order conditions for the patient households are:

$$u_{ct}q_t = u_{ht} + \beta g_C E_t \left(u_{ct+1}q_{t+1}\left(1-\delta_h\right)\right) \quad (1)$$

$$u_{ct} = \beta g_C E_t \left(u_{ct+1}R_t/\pi_{t+1}\right) \quad (2)$$

$$\frac{u_{ct}}{\mathsf{A}_{kt}}\left(1+\frac{\partial\phi_{ct}}{\partial k_{ct}}\right) = \beta g_C E_t\left(u_{ct+1}\left(R_{ct+1}+\frac{1-\delta_k}{\mathsf{A}_{kt+1}}-\frac{\partial\phi_{ct+1}}{\partial k_{ct}}\right)\right) \quad (3)$$

$$u_{ct}\left(1+\frac{\partial\phi_{ht}}{\partial k_{ht}}\right) = \beta g_C E_t\left(u_{ct+1}\left(R_{ht+1}+1-\delta_k-\frac{\partial\phi_{ht+1}}{\partial k_{ht}}\right)\right) \quad (4)$$

$$u_{nct} = u_{ct}w_{ct} \quad (5)$$

$$u_{nht} = u_{ct}w_{ht}. \quad (6)$$

The first-order conditions for the impatient households are:

$$u_{c't}q_t = u_{h't} + \beta' E_t\left(u_{c't+1}\left(q_{t+1}\left(1-\delta_h\right)\right)\right) + E_t\left(\lambda_t\frac{m_t q_{t+1}\pi_{t+1}}{R_t}\right) = 0 \quad (7)$$

$$u_{c't} = \beta' g_C E_t\left(u_{c't+1}\frac{R_t}{\pi_{t+1}}\right) + \lambda_t \quad (8)$$

$$u_{nc't} = u_{c't}w'_{ct} \quad (9)$$

$$u_{nh't} = u_{c't}w'_{ht} \quad (10)$$

where λ_t denotes the multiplier on the borrowing constraint, which is greater than zero in a neighborhood of the equilibrium.

The first-order conditions for the intermediate goods firms will be

$$\left(1-\mu_c\right)\alpha\frac{Y_t}{X_t n_{ct}} = w_{ct} \quad (11)$$

$$\left(1-\mu_c\right)\left(1-\alpha\right)\frac{Y_t}{X_t n'_{ct}} = w'_{ct} \quad (12)$$

$$\left(1-\mu_h-\kappa\right)\alpha\frac{q_t IH_t}{n_{ht}} = w_{ht} \quad (13)$$

$$\left(1-\mu_h-\kappa\right)\left(1-\alpha\right)\frac{q_t IH_t}{n'_{ht}} = w'_{ht} \quad (14)$$

$$\mu_c\frac{Y_t}{X_t k_{ct-1}} = R_{ct} \quad (15)$$

$$\mu_h\frac{q_t IH_t}{k_{ht-1}} = R_{ht} \quad (16)$$

$$\mu_l q_t IH_t = R_{lt} \quad (17)$$

where is the last equation we normalize total land supply l_t to unity.

The budget and borrowing constraints are:

$$c_t + \frac{k_{ct}}{\mathsf{A}_{kt}} + k_{ht} + q_t\left(h_t - (1-\delta_h)\,h_{t-1}\right) = w_{ct}n_{ct} + w_{ht}n_{ht} + f_t - \phi_t$$
$$+\left(R_{ct} + \frac{1-\delta_k}{\mathsf{A}_{kt}}\right)k_{ct-1} + \left(R_{ht} + 1 - \delta_k\right)k_{ht-1} + b_t - \frac{R_{t-1}b_{t-1}}{\pi_t} + R_{lt} \tag{18}$$

where $f_t = (1 - 1/X_t)\,Y_t$, and:

$$c'_t + q_t\left(h'_t - (1-\delta_h)\,h'_{t-1}\right) = w'_{ct}n'_{ct} + w'_{ht}n'_{ht} + b'_t - \frac{R_{t-1}}{\pi_t}b'_{t-1} \tag{19}$$

$$b'_t = mE_t\left(q_{t+1}h'_t\pi_{t+1}/R_t\right). \tag{20}$$

The production functions are:

$$Y_t = \left(\mathsf{A}_{ct}\left(n_{ct}^{\alpha}n_{ct}'^{1-\alpha}\right)\right)^{1-\mu_c}k_{ct-1}^{\mu_c} \tag{21}$$

$$IH_t = \left(\mathsf{A}_{ct}\mathsf{A}_{ht}\left(n_{ht}^{\alpha}n_{ht}'^{1-\alpha}\right)\right)^{1-\mu_h-\mu_l}k_{ht-1}^{\mu_h}. \tag{22}$$

The Phillips curve is:

$$\log\pi_t - \iota_\pi\log\pi_{t-1} = \beta g_C\left(E_t\log\pi_{t+1} - \iota_\pi\log\pi_t\right) - \varepsilon_{\pi X}\log\left(\frac{X_t}{X}\right) + \log\mathsf{u}_t. \tag{23}$$

The Taylor rule is:

$$R_t = (R_{t-1})^{r_R}\left(\pi_t^{r_\pi}\left(\frac{GDP_t}{g_C GDP_{t-1}}\right)^{r_Y}\overline{rr}\right)^{1-r_R}\mathsf{e}_{Rt} \tag{24}$$

where $GDP_t = Y_t + qIH_t$. Two market clearing conditions are

$$C_t + IK_{ct}/\mathsf{A}_{kt} + IK_{ht} = Y_t - \phi_t \tag{25}$$

$$h_t + h'_t - (1-\delta_h)\left(h_{t-1} + h'_{t-1}\right) = IH_t. \tag{26}$$

By Walras' law, $b_t + b'_t = 0$. This set of model equations, together with the definitions (for IK_c, IK_h, GDP_t, f_t, ϕ_t and its derivatives) and the laws of motion for the exogenous shocks, defines a system of 26 equations in the following variables:

Patient households: $c \quad h \quad k_c \quad k_h \quad n_c \quad n_h \quad b$

Impatient households: $c' \quad h' \quad n'_c \quad n'_h \quad b'$

Firms: $IH \quad Y$

Markets/prices: $q \quad R \quad \pi \quad \lambda \quad X \quad w_c \quad w_h \quad w'_c \quad w'_h \quad R_c \quad R_h \quad R_l$

After detrending the variables by their balanced growth trends, we linearize the resulting system around the non-stochastic steady state, and compute the decision rules and the likelihood function using standard solution methods.

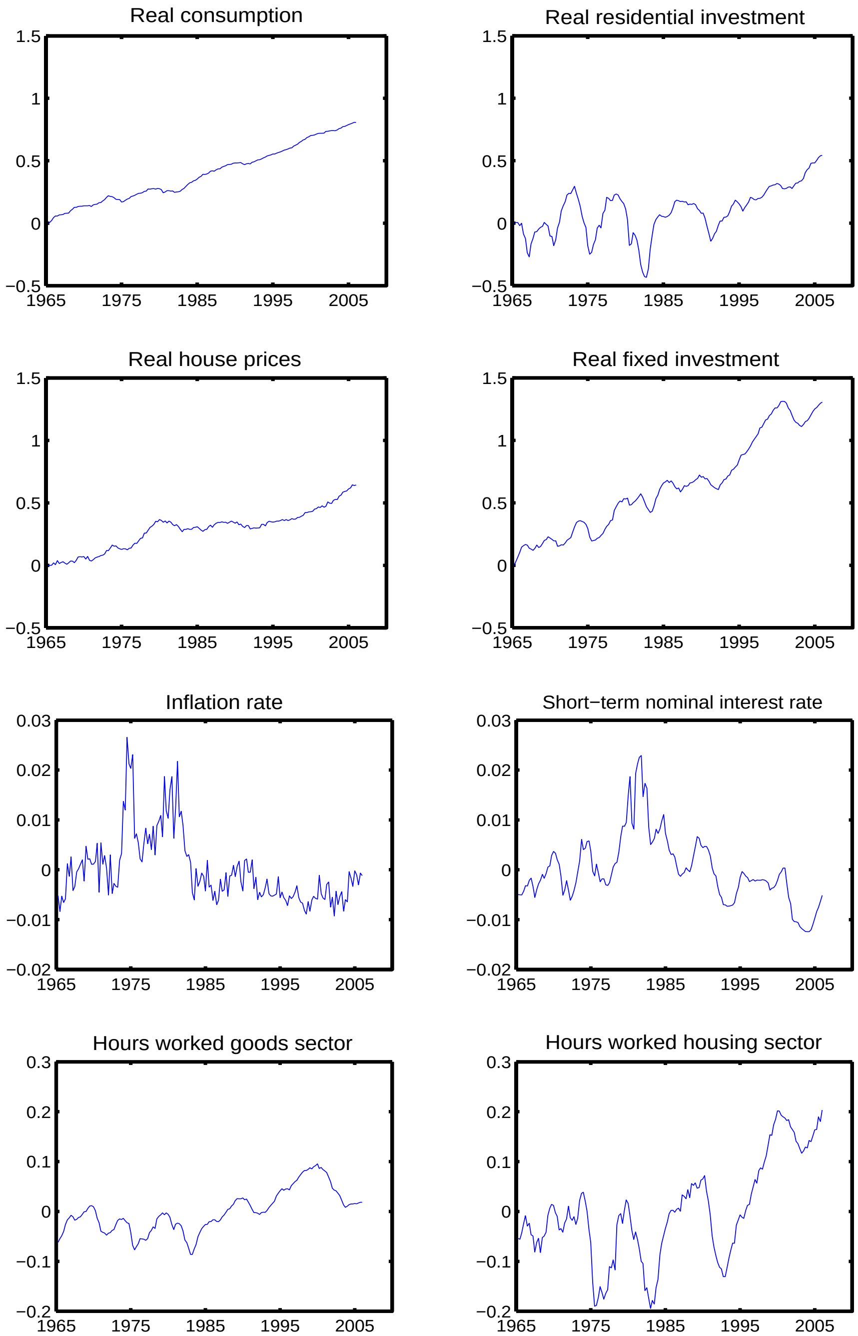

Figure 1 Data

Note: Variables in the top panel (with the exception of real house prices) are divided bycivilian noninstitutional population age 16 and over, log-transformed. The first observation (1965:1) is normalized to zero. Variables in the bottom panel are de-meaned. Hours worked in the two sectors are defined as total hours divided by population.

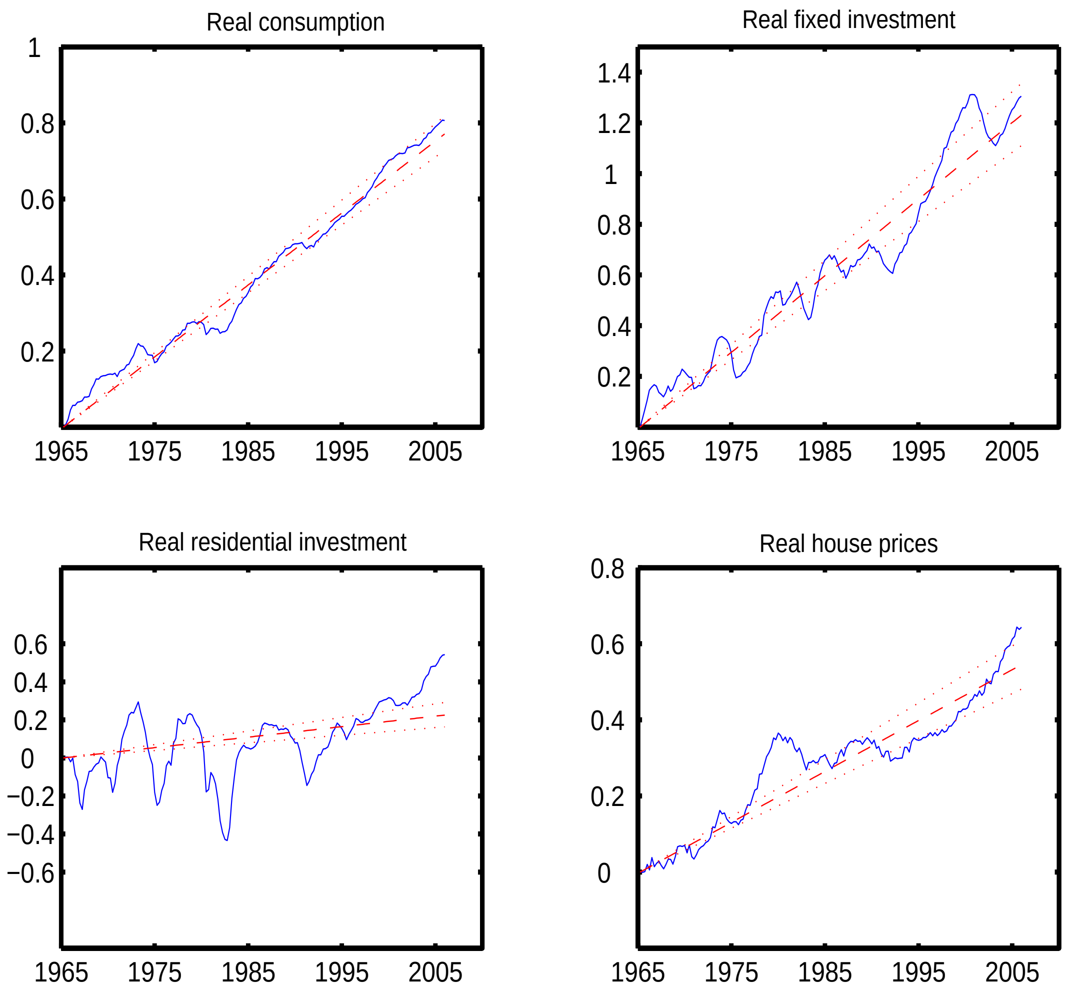

Figure 2 Data and estimated trends

Note: Red dashed line corresponds to the median of the posterior distribution of the trend. Red dotted lines corresponds to 5 and 95 percentiles, blue solid line the data.

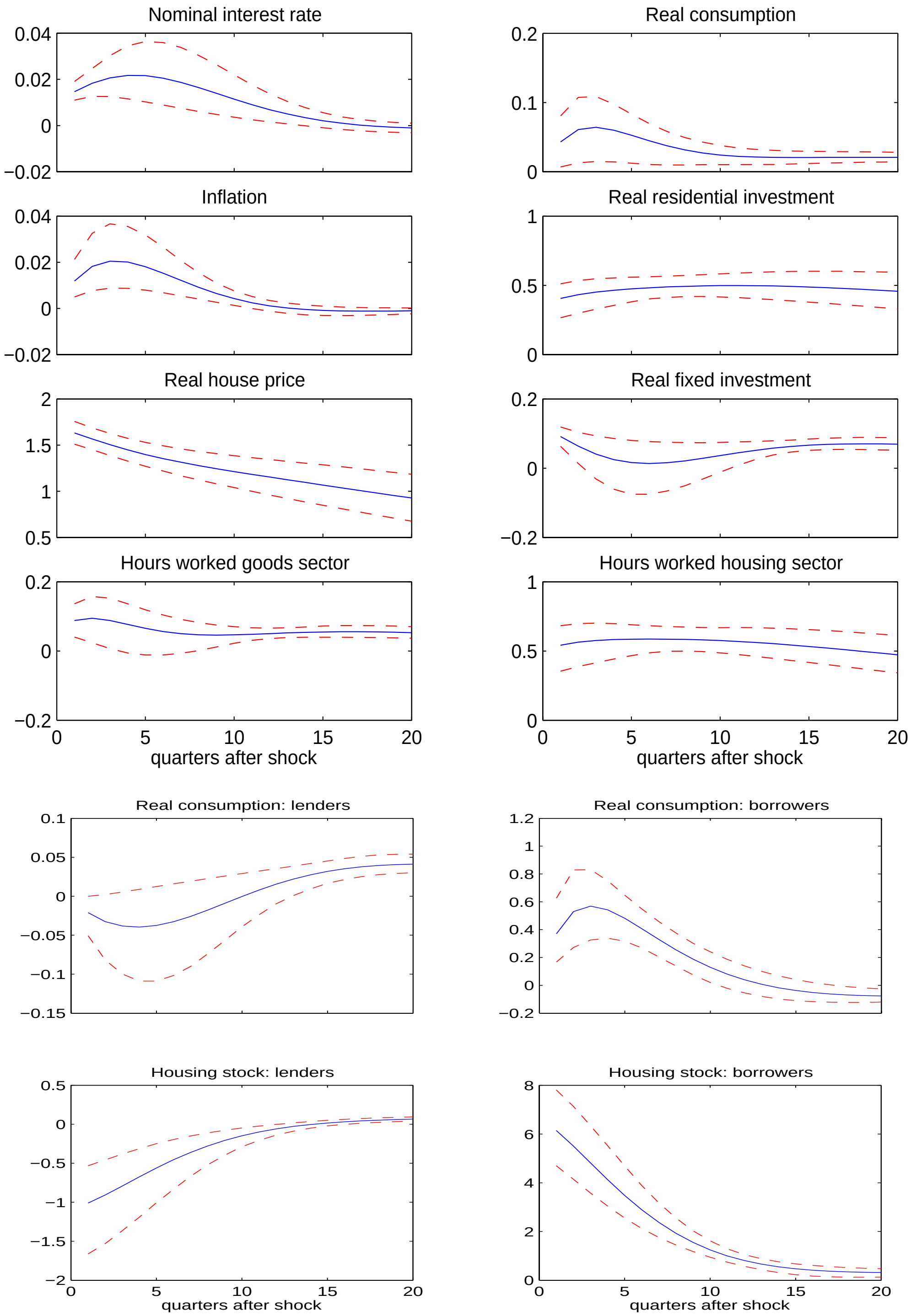

Figure 3 Impulse responses to a positive housing preference shock

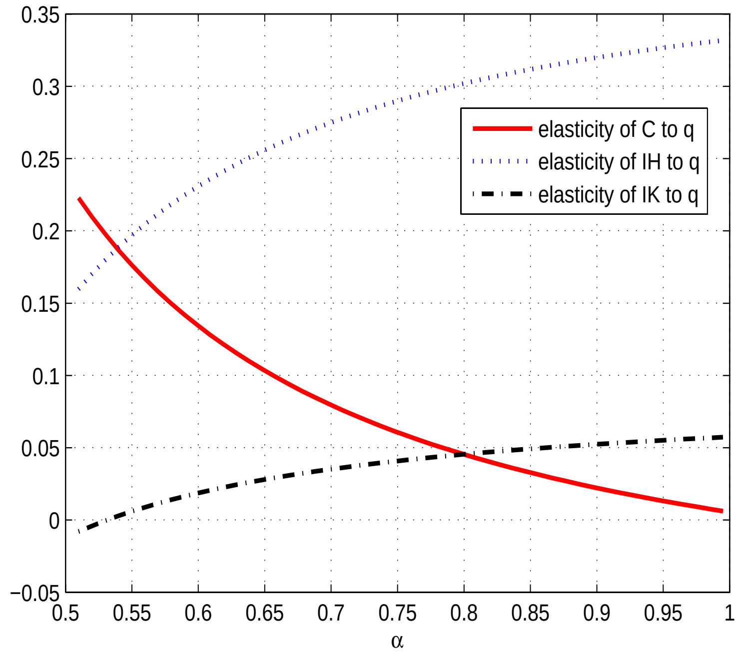

Figure 4 Elasticity of aggregate demand components to real house prices following a housing preference shock: the effect of varying the share of constrained agents

Note: The elasticities are computed as ratios of the four quarters averages of the responses. Results based on the output of the Metropolis algorithm.

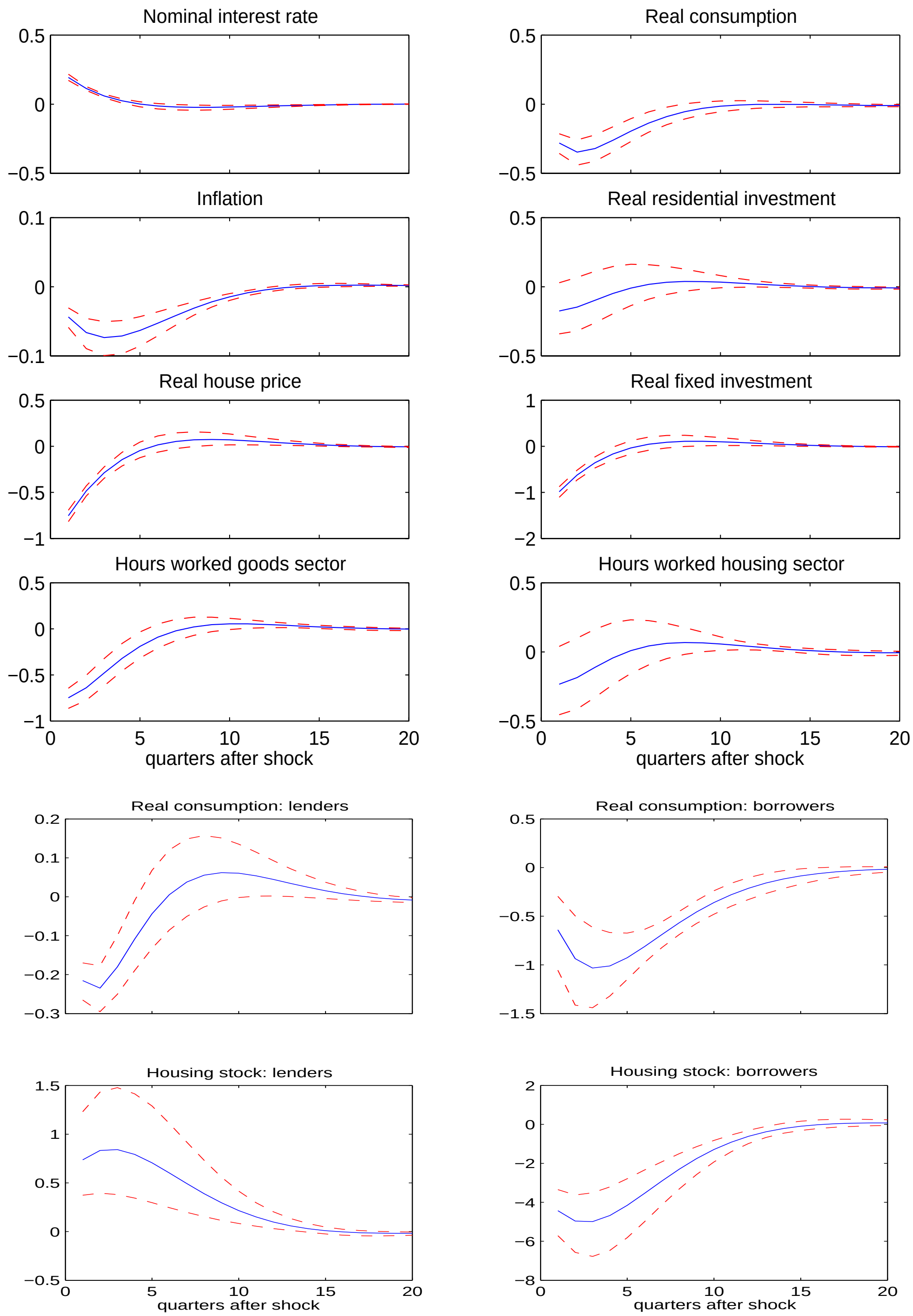

Figure 5 Impulse responses to a negative monetary policy shock

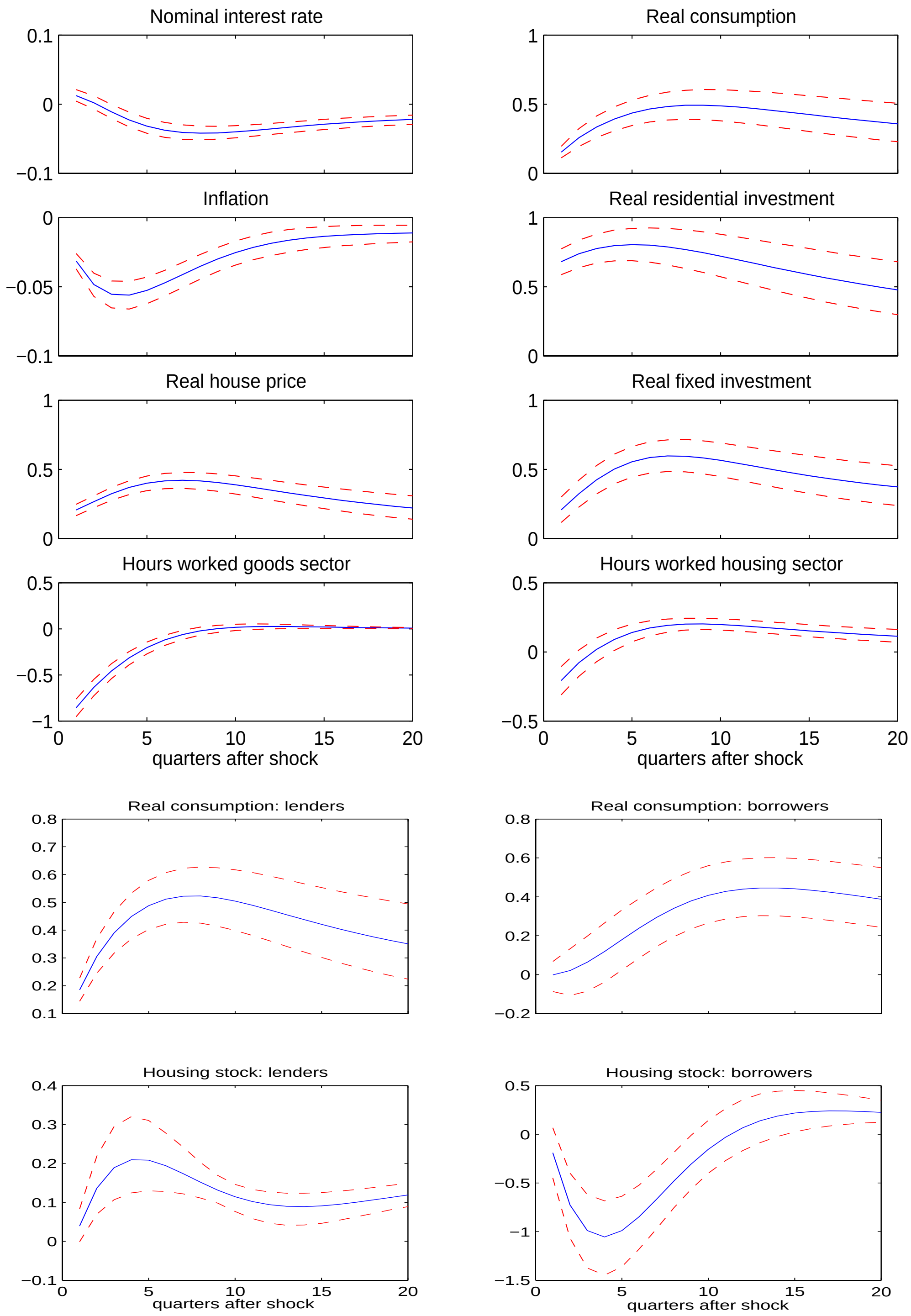

Figure 6 Impulse responses to a positive technology shock in the goods sector

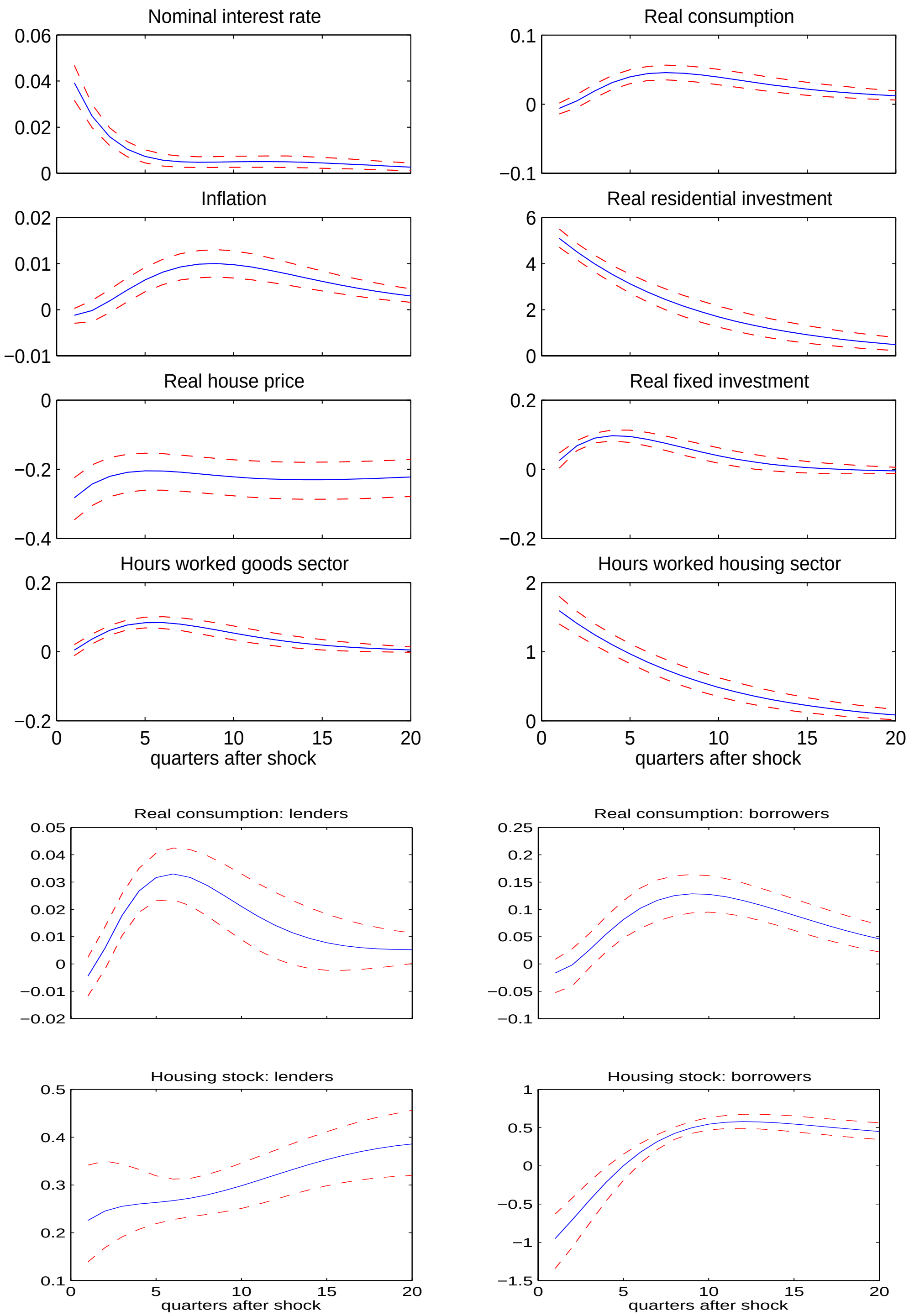

Figure 7 Impulse responses to a positive technology shock in the housing sector

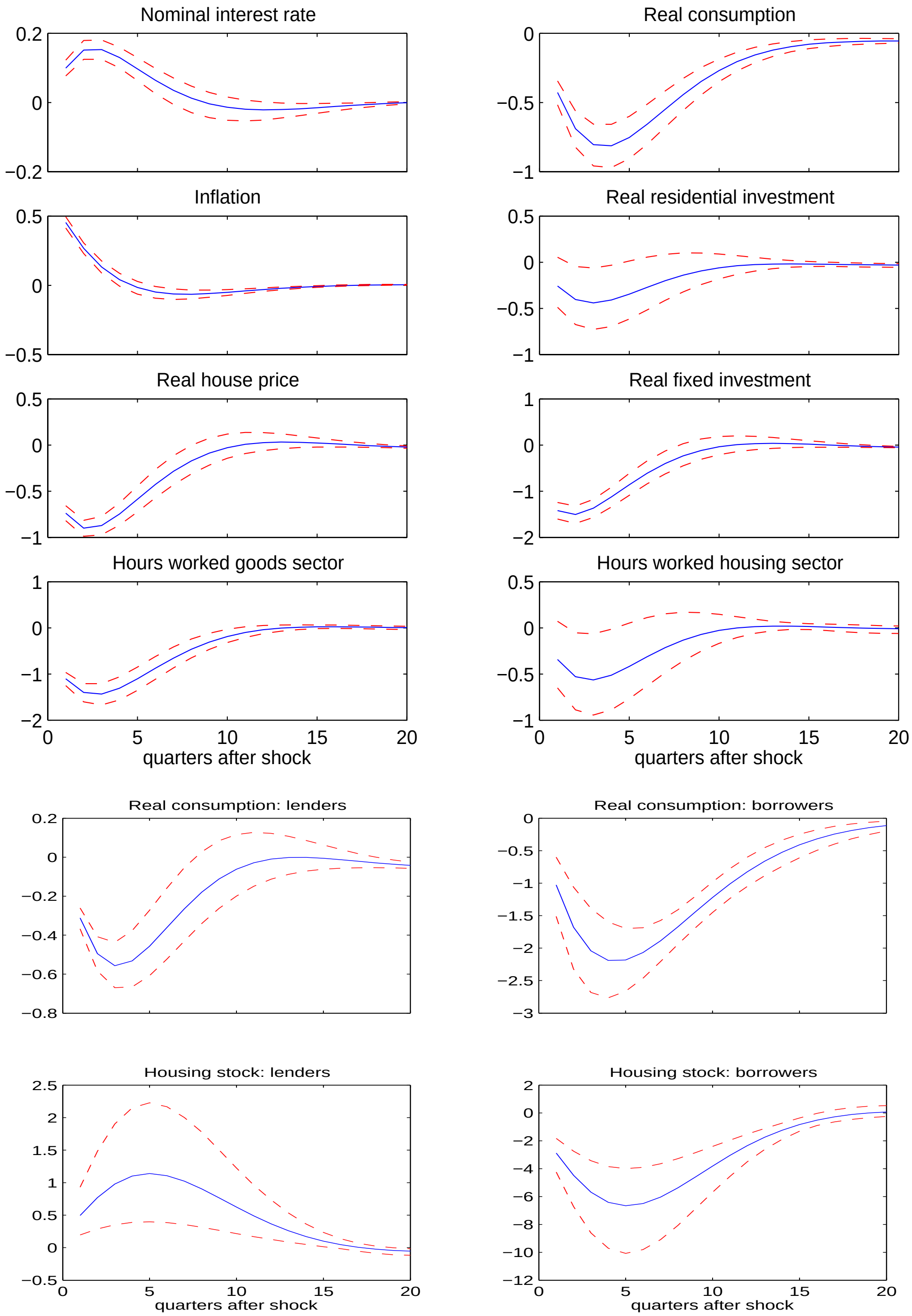

Figure 8 Impulse responses to a negative cost-push shock

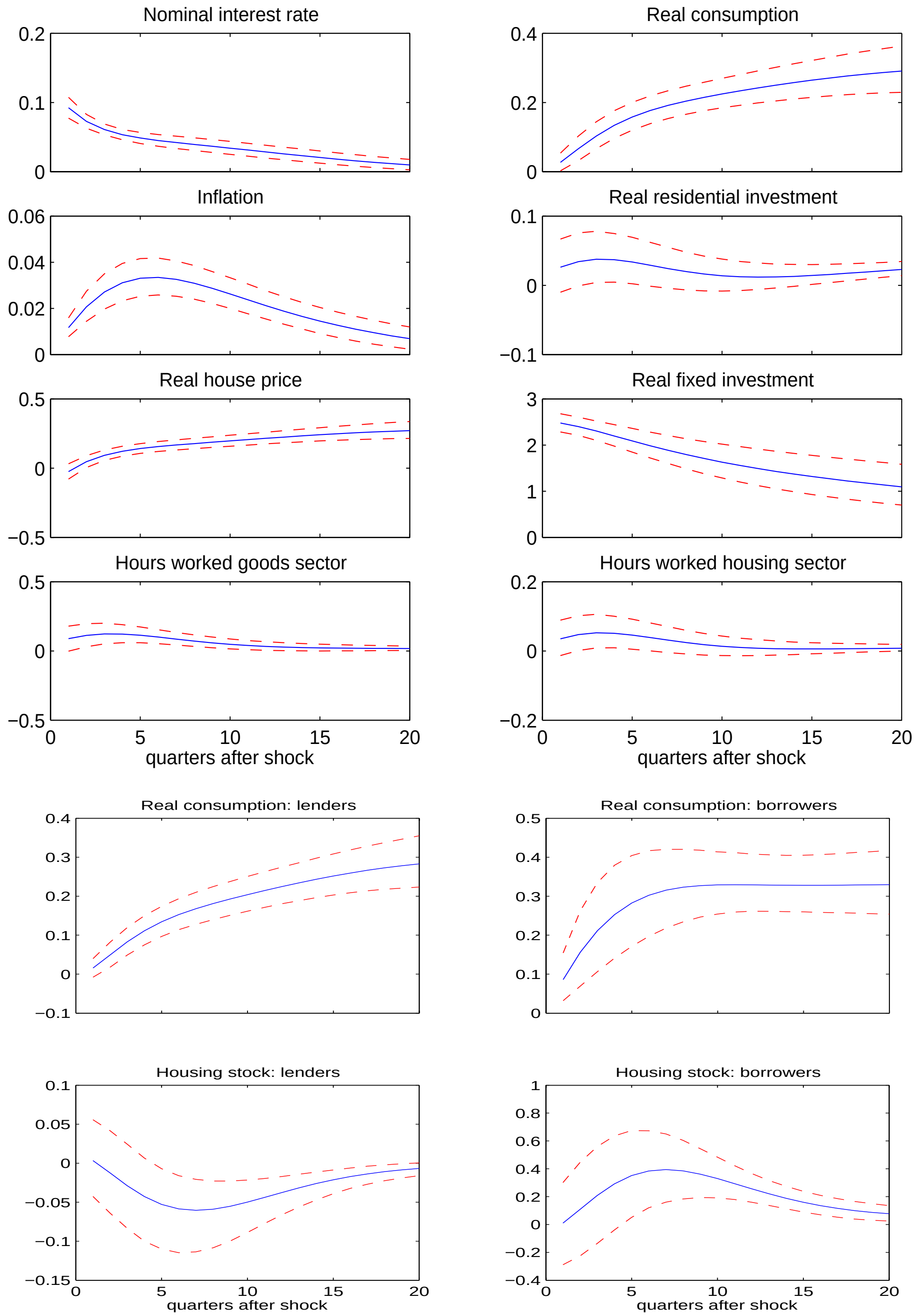

Figure 9 Impulse responses to a positive investment specific technology

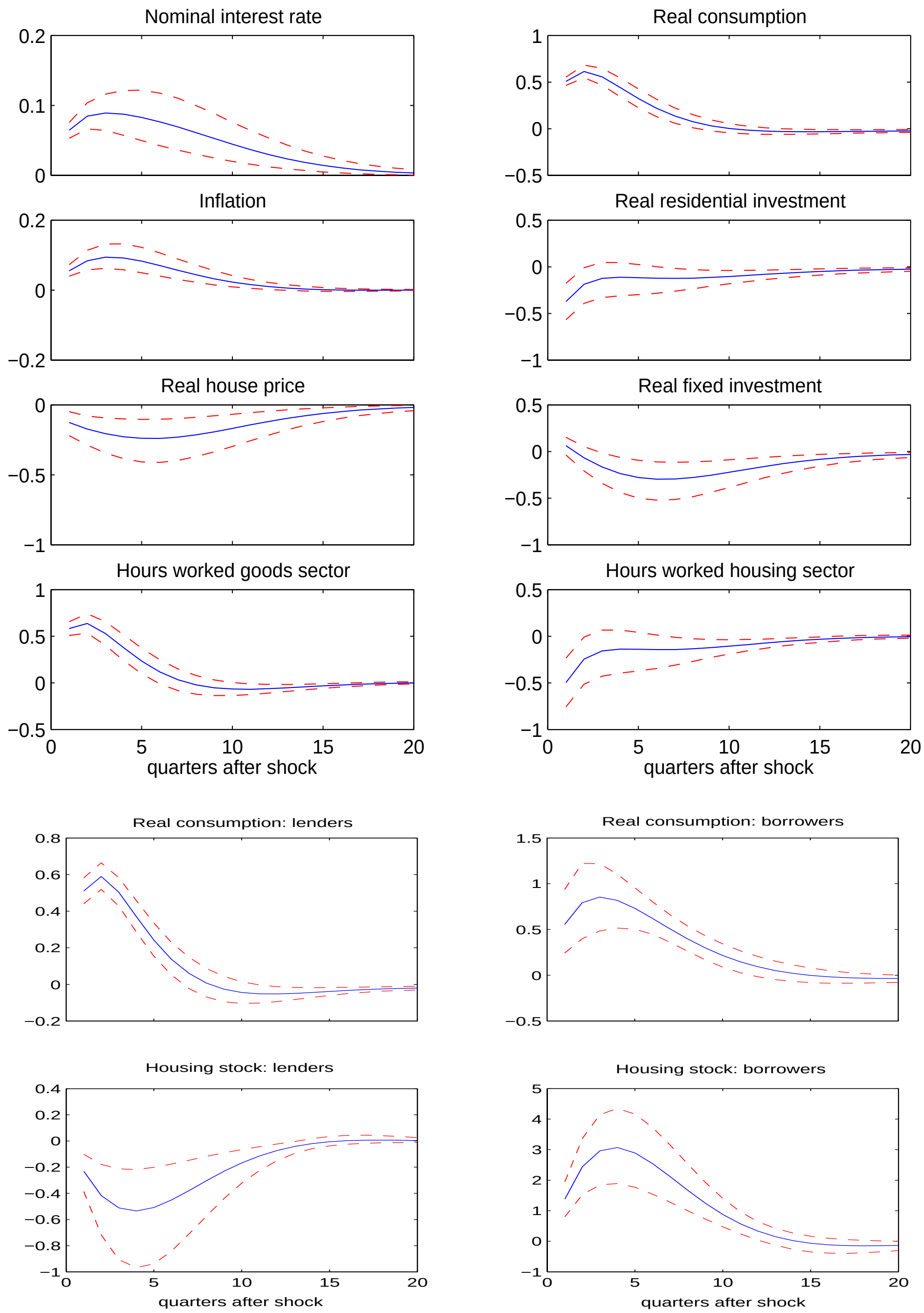

Figure 10 Impulse responses to a positive preference shock

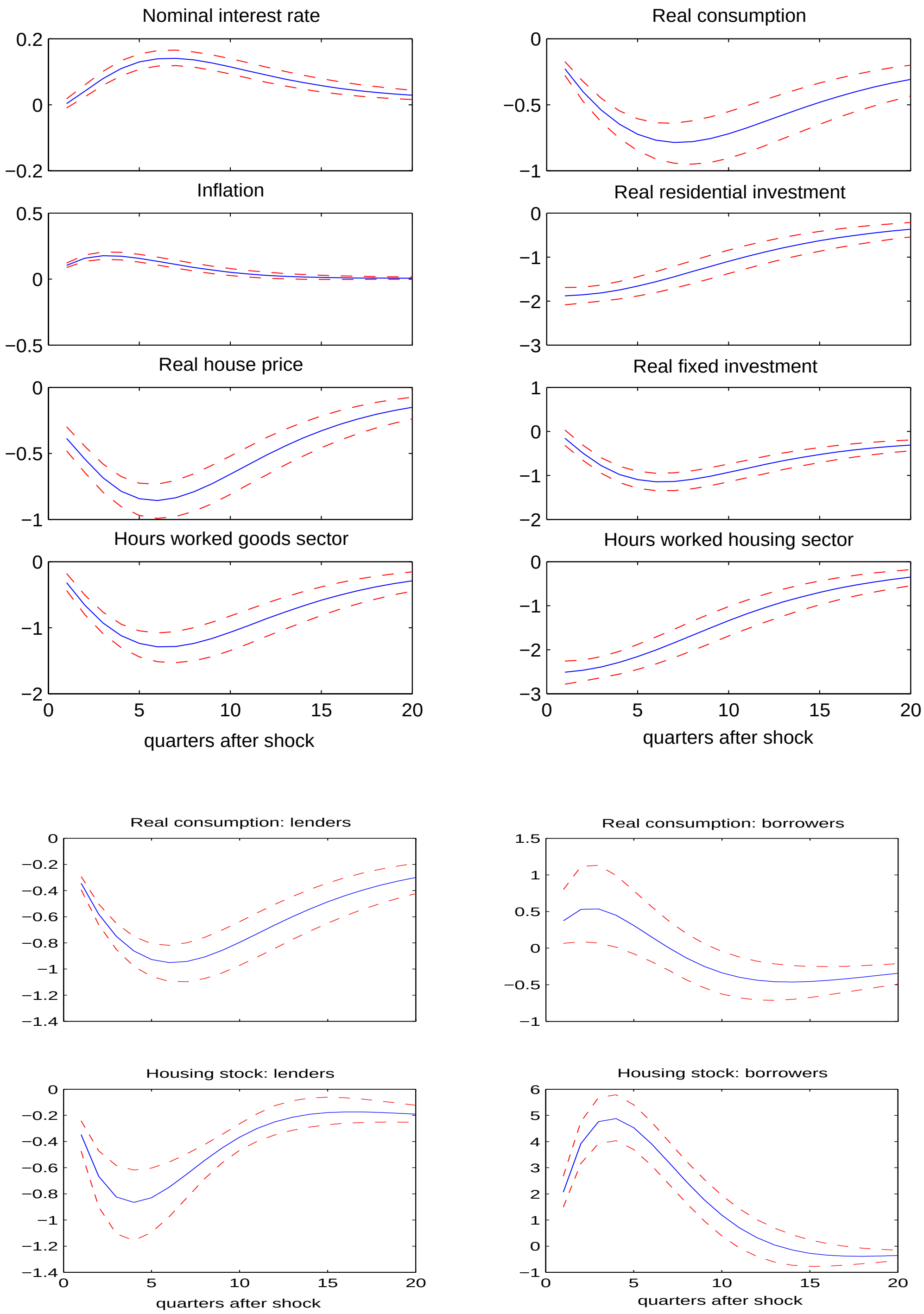

Figure 11 Impulse responses to a negative labor supply shock

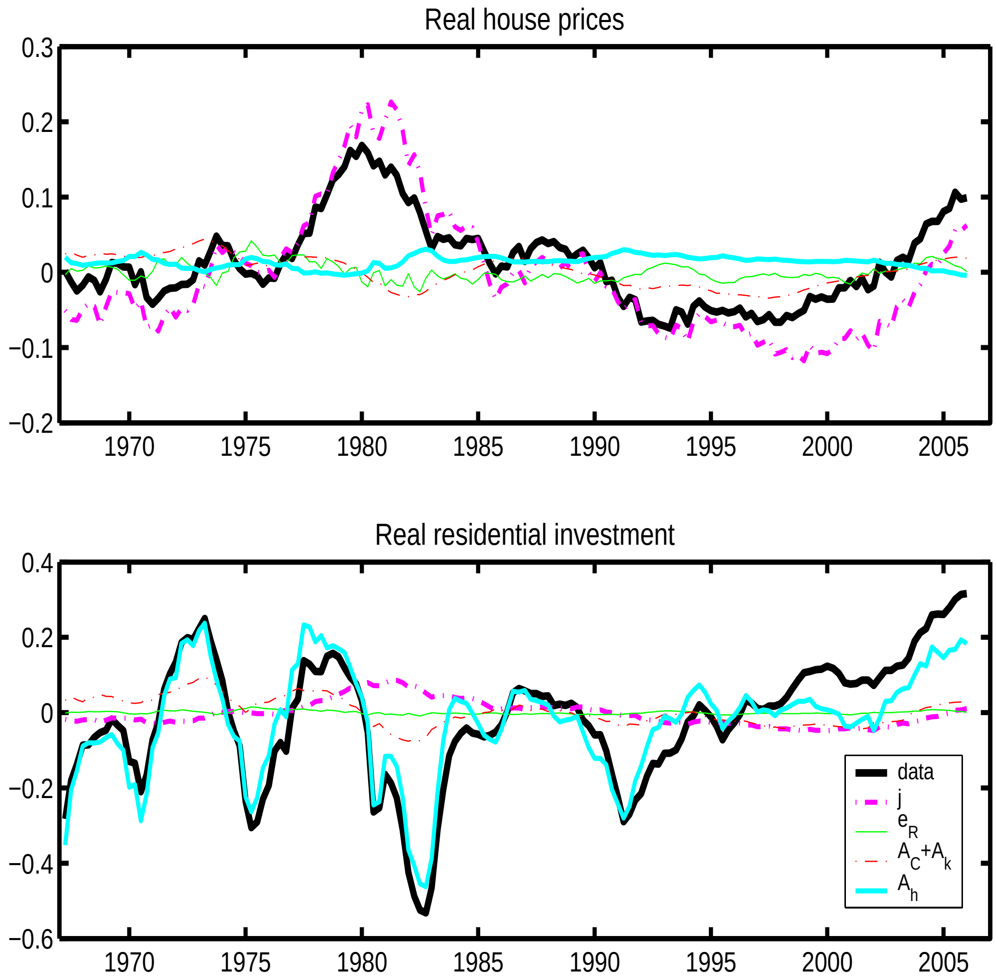

Figure 12 Historical decomposition of housing prices and housing investment

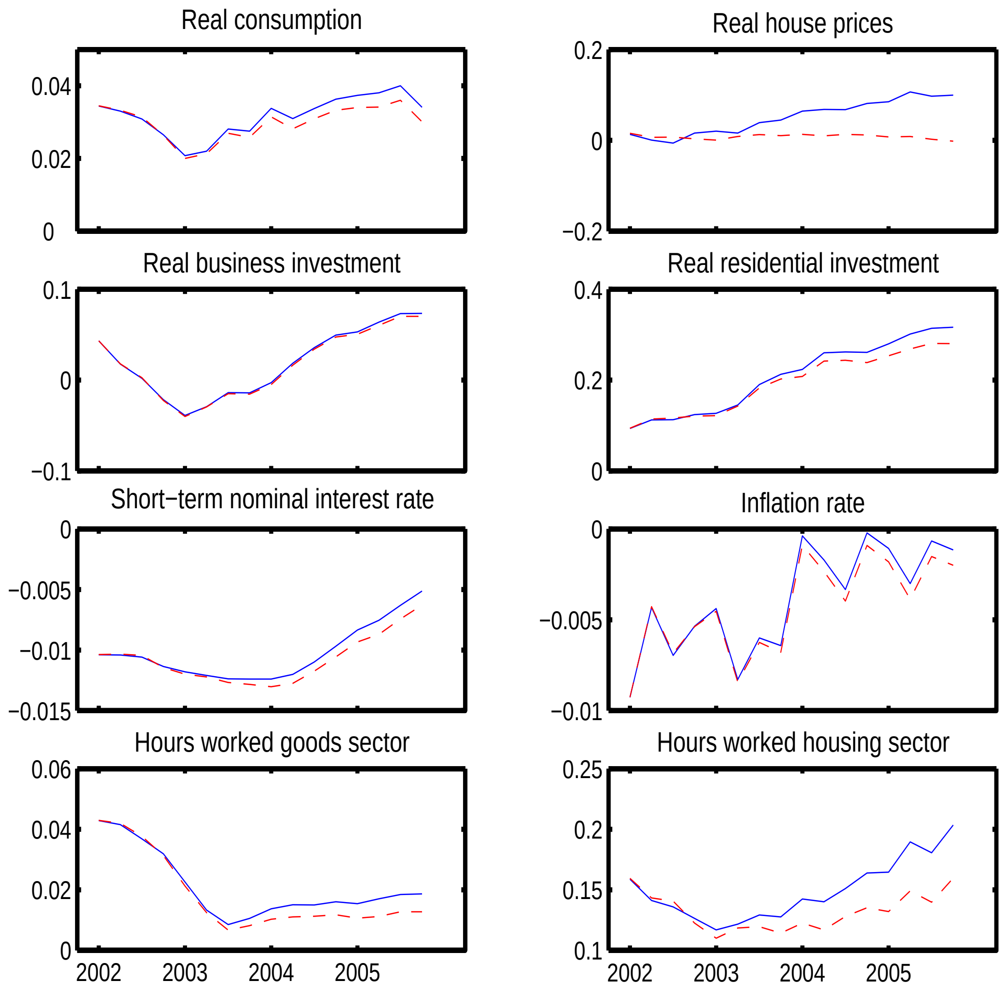

Figure 13 Counterfactual experiment: shutting off housing preference shocks from 2002:1 onwards

Note: Red dotted lines correspond to the path of the variables in the counterfactual experiment. Blue solid line corresponds to the data. In the simulation the mean of the posterior distribution has been used.

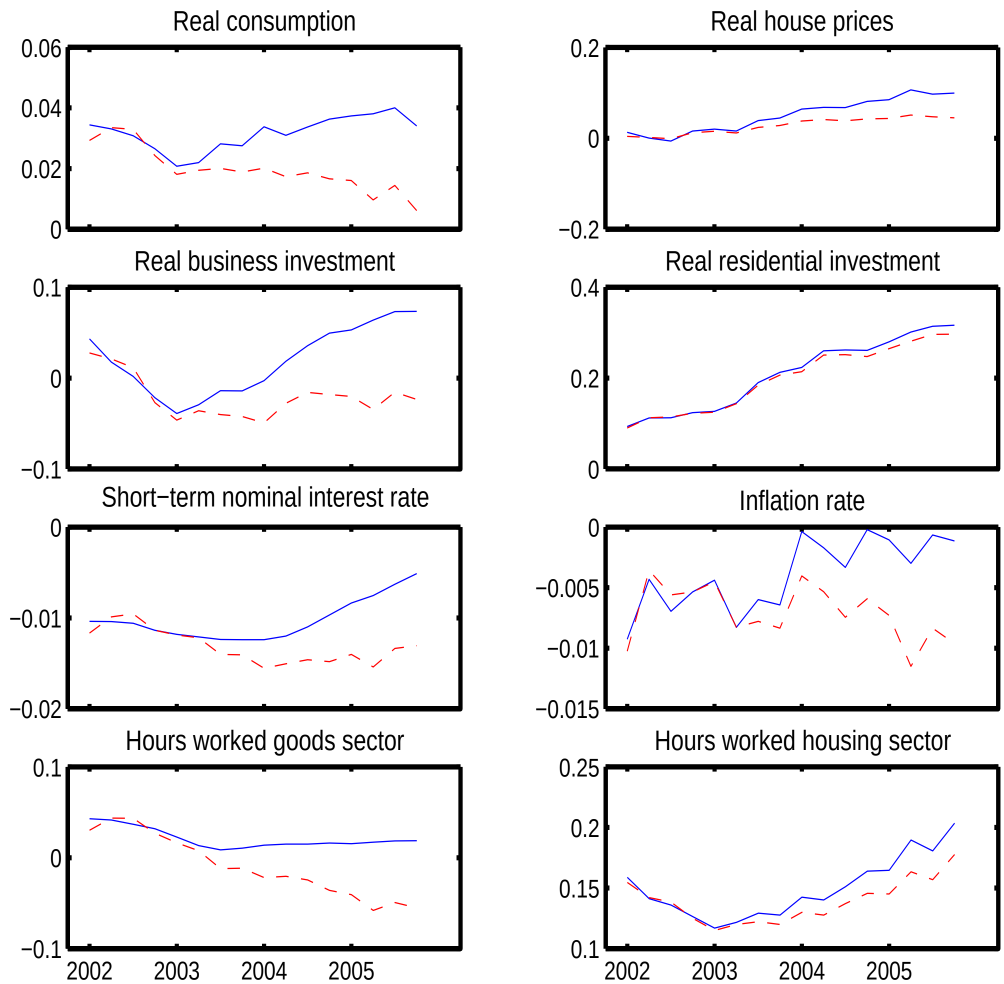

Figure 14 Counterfactual experiment: What if the Federal Reserve had responded to real house prices since 2002:1

Note: Red dotted lines correspond to the path of the variables in the counterfactual experiment. In the simulation the mean of the posterior distribution has been used. The response to real house price has been se to 0.1.

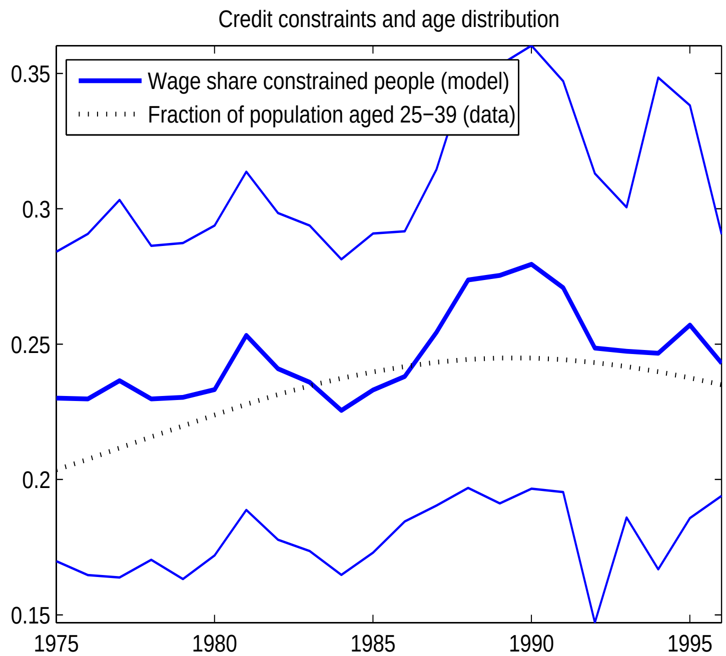

Figure 15 Credit constraints and age distribution of population

Note: Black dotted line corresponds to the share of constrained person in the U.S. Blue solid thick line corresponds to the mean recursive estimates of $(1-\alpha)$, while blue solid thin lines denote the 90 percent probabilty intervals. The model has been estimated recursively over a moving window of 20 years.

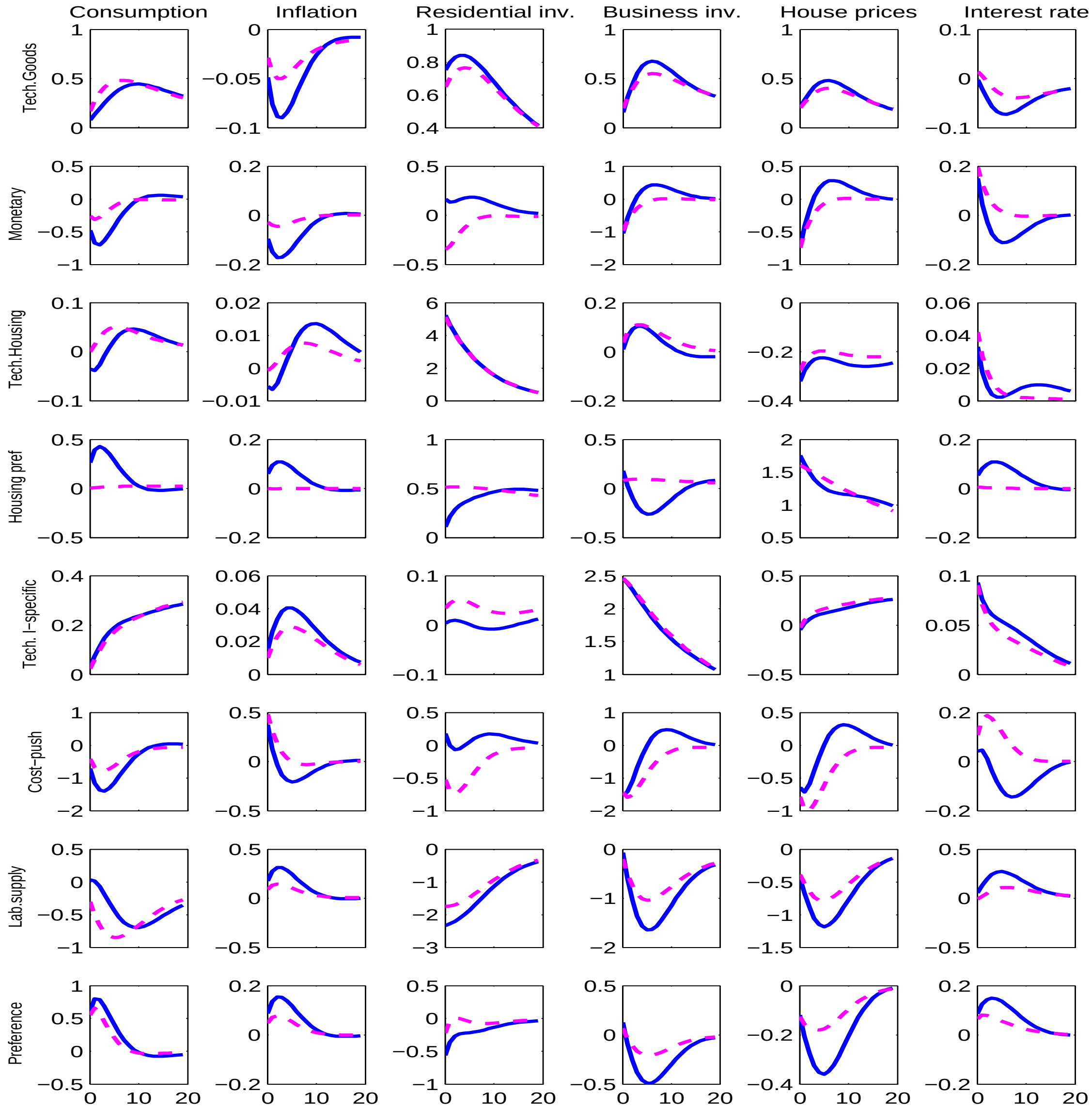

Figure 16 Impulse responses of our model for different values of α, the labor income share of unconstrained agents.

Note: Solid lines: $\alpha = 0.5$; dashed lines: no credit constraints ($\alpha = 1$)

Table 1. Summary statistics for the posterior distribution of the parameters

	posterior					prior		
parameter	2.5	50	97.5	mean	st. dev.	mean	st. dev.	Type
ϵ	0.423	0.533	0.623	0.530	0.052	0.50	0.075	Beta
ϵ'	0.438	0.732	0.888	0.712	0.132	0.50	0.075	Beta
η	0.381	0.601	0.876	0.607	0.126	0.25	0.10	Gamma
η'	0.299	0.456	0.672	0.464	0.094	0.25	0.10	Gamma
ν	-2.894	-2.296	-1.801	-2.306	0.278	-2.0	0.50	Normal
ν'	-3.003	-2.065	-1.177	-2.071	0.468	-2.0	0.50	Normal
$\phi_{k,c}$	20.307	23.436	26.881	23.467	1.704	10.0	2.50	Gamma
$\phi_{k,h}$	9.575	11.832	13.890	11.804	1.103	10.0	2.50	Gamma
α	0.679	0.790	0.867	0.784	0.051	0.70	0.05	Beta
m	0.734	0.790	0.844	0.789	0.028	0.80	0.025	Beta
r_R	0.643	0.689	0.730	0.688	0.022	0.75	0.10	Beta
r_π	1.186	1.318	1.464	1.319	0.072	1.50	0.10	Normal
r_Y	0.277	0.405	0.532	0.406	0.064	0.0	0.10	Normal
θ_π	0.904	0.922	0.937	0.921	0.009	0.75	0.05	Beta
ι_π	0.705	0.848	0.963	0.784	0.051	0.5	0.20	Beta
γ_{AC}	0.0030	0.0032	0.0034	0.0032	0.0001	0.005	0.01	Normal
γ_{AH}	-0.0029	-0.0023	-0.0017	-0.0023	0.0003	0.005	0.01	Normal
γ_{AK}	0.0021	0.0028	0.0035	0.0028	0.0003	0.005	0.01	Normal
ρ_j	0.949	0.972	0.991	0.972	0.011	0.80	0.10	Beta
ρ_{AC}	0.912	0.949	0.977	0.947	0.017	0.80	0.10	Beta
ρ_{AH}	0.839	0.883	0.919	0.882	0.021	0.80	0.10	Beta
ρ_{AK}	0.899	0.937	0.974	0.937	0.019	0.80	0.10	Beta
ρ_z	0.539	0.717	0.858	0.711	0.083	0.80	0.10	Beta
ρ_τ	0.830	0.876	0.915	0.875	0.021	0.80	0.10	Beta
σ_{AC}	0.010	0.011	0.013	0.011	0.001	0.005	0.10	Gamma
σ_{AH}	0.046	0.052	0.058	0.052	0.003	0.005	0.10	Gamma
σ_{AK}	0.021	0.024	0.028	0.024	0.002	0.005	0.10	Gamma
σ_j	0.029	0.049	0.076	0.050	0.012	0.005	0.10	Gamma
σ_u	0.005	0.006	0.007	0.006	0.001	0.005	0.10	Gamma
σ_R	0.002	0.003	0.003	0.003	0.000	0.005	0.10	Gamma
σ_z	0.013	0.018	0.025	0.018	0.003	0.005	0.10	Gamma
σ_τ	0.038	0.051	0.064	0.051	0.007	0.005	0.10	Gamma

Note: Results based on 500,000 draws from the posterior distribution obtained using the Metropolis algorithm.

Table 2. Business cycle properties of the model

	Data	5	50	95
Standard deviation (perc.)				
C	1.23	1.39	1.84	2.46
IH	10.02	5.84	7.05	8.51
IK	4.97	3.57	4.38	5.37
q	1.87	2.39	2.92	3.56
N_c	1.43	2.47	3.17	4.12
N_h	4.08	3.50	4.33	5.36
π	0.40	0.51	0.62	0.74
R	0.32	0.33	0.42	0.52
GDP	4.13	3.06	3.84	4.86
Correlations				
C, GDP	0.86	0.61	0.77	0.87
IK, GDP	0.75	0.39	0.60	0.75
IH, GDP	0.85	0.44	0.62	0.76
q, GDP	0.57	0.49	0.67	0.79
q, C	0.49	0.31	0.55	0.72
q, IH	0.40	-0.10	0.16	0.41
q, IK	0.59	0.26	0.49	0.67
First order correlation				
C	0.87	0.83	0.88	0.91
IH	0.90	0.57	0.68	0.77
IK	0.91	0.65	0.74	0.81
q	0.78	0.65	0.75	0.82
N_c	0.91	0.74	0.82	0.87
N_h	0.89	0.63	0.73	0.81
π	0.47	0.49	0.61	0.71
R	0.81	0.65	0.75	0.82
GDP	0.92	0.72	0.80	0.86
Lead-lag correlations				
IH_{t-1}, GDP_t	0.89	0.24	0.50	0.68
IH_t, GDP_t	0.85	0.44	0.62	0.76
IH_{t+1}, GDP_t	0.67	0.29	0.50	0.66

Note: Results based on 500,000 draws from the posterior distribution. Statistics both in the data and the model are computed on the basis of HP-filtered time series (the smoothing parameter is set to 1600).

Table 3. Decomposition of the asymptotic variance of the forecast error

	j	a_c	a_h	ϵ_R	u	a_k	z	τ
C_t	0.19	21.58	0.07	1.76	15.65	18.68	5.48	30.76
	[0.1,0.4]	[10.8,40.6]	[0.0,0.1]	[0.9,3.1]	[9.8,21.9]	[10.4,35.2]	[3.5,8.0]	[19.1,43.3]
π_t	0.28	3.84	0.16	4.20	52.56	1.81	7.15	28.00
	[0.1,1.1]	[2.9,5.3]	[0.1,0.2]	[2.1,8.0]	[45.2,59.1]	[1.1,3.2]	[3.0,15.1]	[20.2,36.1]
IH_t	5.00	6.47	68.29	0.08	0.64	0.1	0.2	17.0
	[2.8,10.8]	[3.7,11.6]	[59.6,75.5]	[0.0,0.2]	[0.1,1.6]	[0.0,0.2]	[0.0,0.6]	[12.2,23.3]
Q_t	66.41	3.93	4.00	1.45	5.15	5.35	0.57	10.00
	[55.4,78.2]	[2.1,6.9]	[2.2,7.1]	[0.9,2.0]	[3.2,7.3]	[2.8,11.8]	[0.1,2.2]	[5.9,15.2]
R_t	0.66	5.75	0.62	12.66	20.77	8.56	11.78	36.60
	[0.2,2.1]	[4.3,7.7]	[0.0,1.0]	[9.8,15.8]	[15.2,26.3]	[6.0,12.2]	[5.0,25.7]	[26.9,45.3]
IK_t	0.14	5.90	0.05	1.51	8.24	69.70	0.50	11.60
	[0.0,0.3]	[2.8,12.4]	[0.0,0.1]	[0.9,2.20]	[5.0,12.0]	[57.7,82.1]	[0.1,2.1]	[6.2,18.5]
$N_{c,t}$	0.42	5.02	0.17	4.55	32.00	0.32	4.19	52.3
	[0.2,0.8]	[3.5,7.2]	[0.1,0.2]	[3.2,6.8]	[25.9,39.4]	[0.1,0.9]	[3.0,6.1]	[41.8,61.7]
$N_{h,t}$	13.15	0.84	15.26	0.36	2.37	0.0	0.58	65.40
	[8.2,23.4]	[0.5,1.5]	[10.6,20.7]	[0.1,0.9]	[0.3,5.4]	[0.0,0.1]	[0.1,2.5]	[55.1,73.3]

Note: The table reports posterior medians and 90 percent probability intervals (in brackets). Statistics are computed using 500,000 draws.