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Housing collateral and the monetary transmission mechanism*

Karl Walentin and Peter Sellin†

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Abstract

In this paper our main aim is to quantify the role that housing collateral plays for the monetary transmission mechanism. Furthermore, we want to explore the implications of the increase in household indebtedness, and specifically the loan-to-value ratio, in the last two decades. We set up a two sector DSGE model with production of goods and housing. Households can only borrow by using their houses as collateral. The structure of the model closely follows Iacoviello and Neri (2010). To be able to do quantitatively relevant exercises we estimate the model using Bayesian methods on Swedish data for 1986q1-2008q3. We quantify the reinforcement of the monetary transmission mechanism that housing used as collateral implies in the presence of nominal loan contracts. This mechanism functions through the effects of the interest rate on house prices as well as on inflation and thereby the real value of nominal debt. This component of the monetary transmission mechanism becomes stronger the higher the loan-to-value ratio is. A change in the maximum loan-to-value ratio from 85% to 95%, all else being equal, implies that the effect of a monetary policy shock is increased by 4% for inflation, 8% for GDP and 24% for consumption. We conclude that to properly understand the monetary transmission mechanism and its changing nature over time, we need to take into account the effects of housing related collateral constraints.

Keywords: House prices, residential investment, monetary policy, monetary transmission mechanism, collateral constraints, Bayesian estimation.

JEL codes: E21, E32, E44, E52, R21, R31.

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1 Introduction

The role of housing in the macroeconomy has been much discussed both in policy and academic circles recently. An even more topical issue is the relationship between monetary policy and house prices, and in particular the role of monetary policy in the recent house price boom in most OECD countries.

In this paper our aim is to get a quantitative understanding of the role that housing and in particular housing collateral plays for the monetary transmission mechanism, as well as the effects of shocks to housing supply and housing demand on the broader macro economy. Furthermore, we want to explore the implications of the changes in the mortgage contracts during the last decades, in particular increasing loan-to-value (LTV) ratios.

With this aim in mind, we set up a two sector DSGE model that includes production of goods and housing. Households can only borrow by using their houses as collateral. Wages and consumption goods prices are sticky. Trends in house prices, residential investment and other real quantities are determined by sector-specific trends in productivity. The model closely follows Iacoviello and Neri (2010, henceforth IN). The key difference in modelling is that we assume investment adjustment costs instead of capital adjustment costs. We show that investment adjustment costs yield more realistic gradual responses to shocks, in particular to monetary policy shocks.

To be able to perform quantitatively relevant exercises we estimate the model. We perform the estimation using Bayesian methods on Swedish data 1986q1-2008q3. This is an interesting country and time period for studying the relationship between house prices, residential investment and GDP growth as all three of these variables exhibited substantial long-term variation. From an international perspective several aspects of the Swedish housing market are unusually aligned with the assumptions made in a large family of macro-housing models and therefore makes it a suitable country for bringing this type of models to the data.

Two key contributions to the literature on DSGE models with housing collateral are Iacoviello (2005) and Aoki, Proudman and Vlieghe (2004), using collateral constraints and costly external finance respectively. As mentioned above, the model in the present paper is closest to Iacoviello and Neri (2010).[1] We choose to build on this model as it combines the collateral constraint assumption with an explicit modelling of residential investment and therefore is well suited to handle trends in house prices.

[1] A non-exhaustive list of papers that explore housing collateral constraints in a macro setting are Calza, Monacelli and Stracca (2007), Christensen, Corrigan, Mendicino and Nishiyama (2009), Finocchiaro and Queijo von Heideken (2009), Lambertini, Mendicino, and Punzi (2010), Piazzesi and Schneider (2008) and Rubio (2009).

Two papers that set the research questions of our paper in context are Mishkin (2007) and Boivin, Kiley and Mishkin (2009). The first paper describes, and quantifies, the various ways in which housing influences the monetary transmission mechanism. The second paper is a broader analysis of one of the main questions in our paper: how the monetary transmission mechanism has changed over time. Our paper is at the nexus of these two questions: how the monetary transmission mechanism has been affected by changes in the LTV.

The paper proceeds as follows: The remainder of section 1 contains a characterization of the housing sector in Sweden. Section 2 describes the model and section 3 the estimation. Results are discussed in section 4 and section 5 concludes.

1.1 Business cycle characteristics of the housing sector

We start by noting that residential investment is a relatively minor component of GDP in Sweden. It accounts for 3.4% of GDP, or 6.3% of private sector GDP, during our period of study. In Table 1 we document the second moments of residential investment and prices, and in addition business investment for comparison. Note that residential investment is the time series that is most volatile and least correlated with GDP. All three series have high autocorrelation.[2]

	Residential investment	House prices	Business Investment
Standard deviation,%	9.33	4.31	7.22
Autocorrelation	0.93	0.90	0.94
Correlation with GDP	0.46	0.82	0.82

Table 1. Business cycle moments, in percent. Quarterly frequency.

Logged and HP-filtered with the smoothing parameter λ=1600.

In most OECD countries residential investment leads the business cycle (see Chapter 3 in IMF, 2008). In Sweden this is not the case, as can be seen in Figure 1. The figure shows output and real residential investment detrended using a Hodrick-Prescott filter. Note that residential investment seems to lag output. This is confirmed in Figure 2, which shows the cross correlation between the two series. More precisely, the x-axis shows the number of quarters by which real residential investment lags output. This pattern is almost identical to the one reported by IMF (2008) for a longer sample, including the 1970s. Thus the finding that in Sweden residential investment lags output seems to be quite robust and not a special feature of the sample period we have chosen to study. Nevertheless, the pattern is

[2] Additional correlations are presented in section 4.6.1 where data moments and model implied moments are compared.

changing slightly over time, and as can be seen in Figure 1 residential investment did not lag output in the current recession.

The Swedish lead-lag pattern is exactly the opposite to the U.S. pattern. A paper that makes the most out of the fact that residential investment leads output in U.S. data is Leamer (2007) who argues that this lead-lag pattern actually indicates a causal relationship; in his own words: "Housing IS the business cycle". For Sweden there is no *prima facie* reason to believe this, as the lead-lag pattern is the reverse.

Why is Sweden different? Only Italy and to some extent Germany and Norway show a similar pattern. Two possible reasons for the observed pattern is government intervention and a longer time between planning and building than in most other countries. We now elaborate on these two explanations.

The Swedish government has historically intervened to a considerable extent in the residential construction sector, by the use of taxes, subsidies and mandates. During the sample period we study the episode of the late 1980s and early 1990s is especially noteworthy. The tax reform of 1991 drastically lowered marginal tax rates for individuals with moderate to high incomes. The reduction of the tax rate applicable to interest deductions substantially increased the user cost of housing for these groups. In addition to this, the value added tax (VAT) on building material was increased by 12 percent and expenditures on heating and other housing services were no longer exempt from VAT. All these changes in government policy contributed to the decline in residential investment that happened after the business cycle tanked in the early 1990's, and thereby contributed to the lagging behavior of Swedish residential investment.

The planning process consists of a general plan for the area and a detailed plan for the type of buildings to be erected. The planning process is frequently delayed by appeals against the detailed plan. It is not unusual that appeals result in a delay of a couple of years. These issues have been discussed extensively by the OECD, see the report by Hüfner and Lundsgaard (2007).

1.1.1 Additional characteristics of the Swedish housing sector

The type of model we use assumes that mortgages have variable interest rates.[3] For Sweden this assumption is reasonable as the country has an internationally high fraction of mortgages with variable interest rate. The average fraction of variable interest rate loans since 1996 is roughly 50% and even higher in recent years.[4] Furthermore, the loans that have fixed rates are fixed for short horizons - the fraction of loans with interest rates fixed for longer than 5 years is almost negligible. Assenmacher-Wesche and Gerlach (2009) show that the response of GDP and house prices to monetary policy shocks is substantially stronger

[3] For a paper that compares the implications of variable interest rate mortgage contracts and fixed interest rate contracts, see Rubio (2009).

[4] Data on this fraction before 1996 is not available, but most certainly it was substantially lower as variable rate loans were not introduced until the late 1980's.

in countries with a high fraction of variable interest rate loans.

An additional reason why Sweden might conform more to the assumptions made in this family of models is that the rental housing market is very rigid. Because of regulations (rent control etc) it is extremely hard to find an apartment to rent, at least in the three major metropolitan areas, so the assumption of no substitution between owner-occupied and rented housing is approximately satisfied.

Finally, Swedish personal bankruptcy law is stricter than e.g. U.S. law - there is basically no way to walk away from personal debt. This removes a non-linear decision problem from the economy, and makes it easier to model with standard linear methods.

2 Model

2.1 Overview

There are two production sectors: The non-housing sector combines capital and labor to produce a good that can be used for consumption, as production capital, or as an intermediate input in housing production. The housing sector combines capital, labor, land and the intermediate good to produce new housing. Each period an endowment of size unity of land is available.

The financial constraint in the model applies to households. They can only borrow up to a fixed fraction of the expected next period value of their house. Loans are in nominal terms and we thereby allow for the debt-deflation mechanism described by Fisher (1933). This mechanism consists of the wealth redistribution effect that surprise inflation has on the real value of debt when loan contracts are in nominal terms.

There are two types of households, patient and impatient households. The only fundamental difference between them is the subjective discount factor. In equilibrium, impatient households are always collateral constrained and own only their own house. Patient households, on the other hand, own all the business capital in the economy and lend to the impatient households.

2.2 Households

Let primes denote variables and parameters related specifically to impatient households. For patient households expected lifetime utility is given by

$$E_0 \sum_{t=0}^{\infty} (\beta G_c)^t z_t \begin{pmatrix} \Gamma_c \log (c_t - \varepsilon G_c c_{t-1}) + j_t \log h_t - \\ \frac{\tau_t}{1+\eta} \left(n_{c,t}^{1+\xi} + n_{h,t}^{1+\xi} \right)^{\frac{1+\eta}{1+\xi}} \end{pmatrix} \tag{1}$$

and for impatient households by

$$E_0 \sum_{t=0}^{\infty} \left(\beta' G_c\right)^t z_t \begin{pmatrix} \Gamma_c' \log\left(c_t' - \varepsilon' G_c c_{t-1}'\right) + j_t \log h_t' - \\ \frac{\tau_t}{1+\eta'} \left(\left(n_{c,t}'\right)^{1+\xi'} + \left(n_{h,t}'\right)^{1+\xi'}\right)^{\frac{1+\eta'}{1+\xi'}} \end{pmatrix} \tag{2}$$

where c, h, n_c and n_h denote consumption, housing services, hours worked in the goods sector and hours worked in the housing sector, respectively. z_t is a time preference shock, j_t a shock in the demand for housing and τ_t a labor supply shock. ε measures the degree of habit formation in consumption goods. The subjective discount factors are β and β' where $\beta > \beta'$. Moreover, η denotes the inverse Frisch elasticity of labor supply. Note that $\xi > 0$ implies that households prefer to spread their working hours to both sectors (see Horvath, 2000), or more loosely, is a measure of the labor immobility between sectors. Finally, G_C is the gross growth rate of consumption in steady state and Γ_c and Γ_c' are scaling factors, defined in section A.3, that ensures stationarity of the marginal utility of consumption. Details about the shock processes are described in section 2.6. The preference specification implies that the expenditure shares of a household for consumption goods and housing, respectively, are stationary but vary with j_t. The only way to obtain housing services is to own a house. No rental market for housing exists.

In equilibrium patient households own all the capital, as well as all the land. The land endowment has been normalized to unity. They choose the capital utilization rate and rent out capital services to firms. They maximize their utility (1) subject to the following budget constraint:[5]

$$\begin{aligned} & c_t + i_{ct}/A_{kt} + i_{ht} + p_t^{kc}\Delta k_{ct} + p_t^{kh}\Delta k_{ht} + o_t + q_t\left(h_t - \left(1-\delta_h\right)h_{t-1}\right) = \\ & \frac{w_{ct}}{X_{wct}} n_{ct} + \frac{w_{ht}}{X_{wht}} n_{ht} + Div_t + R_{ct} z_{ct} k_{ct-1} - p_t^{kc} a(z_{ct}) k_{ct-1} + R_{ht} z_{ht} k_{ht-1} \\ & - p_t^{kh} a(z_{ht}) k_{ht-1} + p_{ot} o_t + b_t - \frac{R_{t-1}}{\pi_t} b_{t-1} + R_{lt} \end{aligned} \tag{3}$$

where i_{ct} and i_{ht} denote investment in capital for each of the two production sectors, Δk_{ct} and Δk_{ht} denotes capital traded in each sector (with zero trade in equilibrium). The consumption good is the numeraire, and p_t^{kc} and p_t^{kh} denote the prices of the two different types of capital. δ_{kc} and δ_{kh} are the respective depreciation rates for capital, and δ_h the depreciation rate of the housing stock. o_t denotes intermediate inputs in housing production, q_t is the real house price. w_{ct} and w_{ht} denote wages in two sectors and n_{ct} and n_{ht} the corresponding hours of work. X_{wct} and X_{wht} are wage markups accruing to labor unions, Div_t denotes profits from retail firms and lump-sum payments from labor unions corresponding to the wage markups, R_{ct}, R_{ht} and R_{lt} are rental rates, z_{ct} and z_{ht} capital utilization rates, and $a(z_{ct})$ and $a(z_{ht})$ utilization costs in terms of capital goods. b_t denotes end-of-period bond holdings. Note that the risk-free interest rate R_{t-1} is in nominal terms, and the ex-post

[5] This maximization is also subject to a collateral constraint analogous to the one for impatient households. In equilibrium, because of $\beta > \beta'$, the collateral constraint is never binding for patient households.

real return is therefore obtained by dividing with the inflation rate π_t. Letting bonds have nominal payoffs is empirically well founded and allows for the debt-deflation mechanism as described by Fisher (1933). The mechanism is generated by the fact that surprise changes in inflation affect the real value of debt, and thereby implies a wealth transfer between lenders and debtors.

Impatient households maximize their utility (2) under two constraints. First, the budget constraint:

$$c_t' + q_t \left(h_t' - (1-\delta_h)\, h_{t-1}' \right) = \frac{w_{ct}'}{X_{wct}} n_{ct}' + \frac{w_{ht}'}{X_{wht}} n_{ht}' + Div_t + b_t' - \frac{R_{t-1}}{\pi_t} b_{t-1}' \qquad (4)$$

Second, the collateral constraint:

$$b_t' \leq m E_t \left\{ q_{t+1} h_t' \pi_{t+1} / R_t \right\} \qquad (5)$$

which follows from the fact that impatient households only can promise to repay up to a fraction m of the expected next period value of their house. This type of collateral constraint, with the appropriate collateral being the expected next period value of the asset, can be derived from a limited contract enforceability problem, as in Lorenzoni and Walentin (2007). For small enough shocks around the steady state the collateral constraint holds with equality, as the impatient households, at the market clearing interest rate R_t, always would like to borrow the maximum amount to consume more today rather than in the future.

2.3 Firms and Technology

We assume there are two types of firms. The first type is competitive producers of the homogenous good that use capital and labor to produce the non-housing good, Y_t, and capital, labor, land and the intermediate input to produce new houses, NH_t. They maximize the following profit function:

$$\frac{Y_t}{X_t} + q_t NH_t - \left(\sum_{i=c,h} w_{i,t} n_{i,t} + \sum_{i=c,h} w_{i,t}' n_{i,t}' + R_{ct} z_{ct} k_{c,t-1} + R_{ht} z_{ht} k_{h,t-1} + R_{lt} + p_{ot} o_t \right)$$

subject to the production technologies for goods and new houses respectively:

$$\begin{aligned} Y_t &= \left(A_{c,t} \left(n_{c,t}^{\alpha} \left(n_{c,t}' \right)^{1-\alpha} \right) \right)^{1-\mu_c} \left(z_{c,t} k_{c,t-1} \right)^{\mu_c} \\ NH_t &= \left(A_{h,t} \left(n_{h,t}^{\alpha} \left(n_{h,t}' \right)^{1-\alpha} \right) \right)^{1-\mu_h-\mu_o-\mu_l} \left(z_{h,t} k_{h,t-1} \right)^{\mu_h} o_t^{\mu_o} l_{t-1}^{\mu_l} \end{aligned}$$

where $A_{c,t}$ is the productivity in the goods sector and $A_{h,t}$ the productivity in the housing sector. α is the labor income share of patient households. Note that labor input from the two types of households is assumed to be complementary.

We assume investment adjustment costs of the type introduced in Christiano, Eichenbaum and Evans (2005). Regarding time notation, we use the time subscript from the period a quantity is determined, which is why $k_{c,t-1}$ is used for production in period t. The law of motion for capital in the two respective production sectors are:

$$k_{ct} = (1-\delta_{kc})\, k_{ct-1} + F(i_{ct}, i_{ct-1}) \tag{6}$$

$$k_{ht} = (1-\delta_{kh})\, k_{ht-1} + F(i_{ht}, i_{ht-1}) \tag{7}$$

where the investment adjustment cost function $F(\cdot,\cdot)$ is defined in section A.2 and its parameters are allowed to be different between sectors.

The second type of firm is monopolistically competitive retailers that costlessly differentiates the homogenous good. These firms buy homogenous goods at the price P_t^w and sell them at the price $P_t = X_t P_t^w$, where X_t is the markup. Retailers face Calvo frictions in their price setting, and get to set a new price with a fixed probability $1-\theta_\pi$. The remaining fraction θ_π of firms partially index their prices, by a fraction ι_π, to past inflation.[6] We allow for an i.i.d. cost-push shock to enter directly in the Phillips curve, as in Smets and Wouters (2007). The resulting Phillips curve is:

$$\log \pi_t - \iota_\pi \log \pi_{t-1} = \beta G_C(E_t \log \pi_{t+1} - \iota_\pi \log \pi_t) - \varepsilon_\pi \log\left(\frac{X_t}{X}\right) + \log e_{p,t} \tag{8}$$

Nominal wages are sticky in an analogous way to prices. Households supply labor to labor unions that differentiate it and set sticky wages.[7] A union is allowed to set wages optimally in a given period with probability θ_w. Partial indexation to past inflation is applied to the remaining $1-\theta_w$ fraction of wages. The resulting wage equations for each sector-household pair is:

$$\omega_{ct} - \iota_{wc} \log \pi_{t-1} = \beta G_C(E_t \omega_{ct+1} - \iota_{wc} \log \pi_t) - \varepsilon_{wc} \log\left(\frac{X_{wct}}{X_{wc}}\right)$$

$$\omega'_{ct} - \iota_{wc} \log \pi_{t-1} = \beta' G_C(E_t \omega'_{ct+1} - \iota_{wc} \log \pi_t) - \varepsilon'_{wc} \log\left(\frac{X_{wct}}{X_{wc}}\right)$$

$$\omega_{ht} - \iota_{wh} \log \pi_{t-1} = \beta G_C(E_t \omega_{ht+1} - \iota_{wh} \log \pi_t) - \varepsilon_{wc} \log\left(\frac{X_{wht}}{X_{wh}}\right)$$

$$\omega'_{ht} - \iota_{wh} \log \pi_{t-1} = \beta' G_C(E_t \omega'_{ht+1} - \iota_{wh} \log \pi_t) - \varepsilon'_{wc} \log\left(\frac{X_{wht}}{X_{wh}}\right)$$

where ω_{it} denotes log nominal wage inflation, i.e. $\omega_{it} = w_{it} - w_{it-1} + \pi_t$. $\varepsilon_{wc}, \varepsilon'_{wc}, \varepsilon_{wh}, \varepsilon'_{wh}$

[6] We consider a steady state inflation of zero, so even with partial or no indexation there is no price dispersion in steady state.

[7] Labor packers then assemble this differentiated labor into to the homogenous composites n_c, n_h, n'_c and n'_h.

are functions of the underlying parameters and are defined in the appendix.

In addition to the standard reasons for assuming price stickiness for the consumption good and wage stickiness in both sectors we note that this is a necessary condition for getting comovement between production in the two sectors, as observed empirically.[8]

2.4 Monetary Policy

The nominal interest rate follows a Taylor rule that is equivalent to IN, but with an explicit inflation target as in Adolfson *et al.* (2005):

$$\begin{aligned}\log\left(\frac{R_t}{R}\right) &= \rho_R \log\left(\frac{R_{t-1}}{R}\right) + (1-\rho_R)\left[\log\left(\frac{\bar{\pi}_t}{\bar{\pi}}\right) + r_\pi \log\left(\frac{\pi_t}{\bar{\pi}_t}\right)\right] + \\ &\quad + r_{\Delta y}\Delta\log\left(\frac{GDP_t}{GDP}\right) + e_{r,t}. \end{aligned} \quad (9)$$

where GDP_t is the sum of the value added of the two sectors at steady state house prices, $GDP_t = Y_t + \bar{q}NH_t - o_t$. ρ_R is the degree of interest rate smoothing, r_π measures the interest rate response to inflation. $r_{\Delta y}$ denotes the response to deviation of GDP from its steady state growth rate. $e_{r,t}$ is the i.i.d. monetary policy shock and $\bar{\pi}_t$ is the time-varying inflation-target that captures persistent deviations of inflation from its steady state.

2.5 Market Clearing

Market clearing for goods imply:

$$c_t + c'_t + i_{ct}/A_{kt} + i_{ht} + o_t = Y_t$$

Similarly for houses:

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

Finally, we assume zero net bond supply. Bond market clearing therefore implies:

$$b_t + b'_t = 0$$

2.6 Shocks

Below we describe the processes for the exogenous shocks in the model. All innovations are denoted by e, with a subscript, and the standard deviations of these innovations are

[8] This is generally aknowledged in the durable goods literature, and was recently emphasized to be true also in settings with collateral constraints by Sterk (2009).

denoted by σ with the corresponding subscript. The preference shocks are AR(1) processes:

$$\begin{aligned}\log z_t &= \rho_z \log z_{t-1} + e_{z,t} \\ \log j_t &= \rho_j \log j_{t-1} + \left(1-\rho_j\right) \log j + e_{j,t} \\ \log \tau_t &= \rho_\tau \log \tau_{t-1} + e_{\tau,t}\end{aligned}$$

As in Adolfson *et al.* (2005) the inflation target follows

$$\log \bar{\pi}_t = \rho_{\bar{\pi}} \log \bar{\pi}_{t-1} + e_{s,t}.$$

As mentioned above, the cost-push shock $e_{p,t}$ and the monetary policy shock $e_{r,t}$ are i.i.d.

2.6.1 Technology shocks and trends

We allow for three productivity processes: (consumption) goods productivity, housing productivity and non-residential investment-specific technology. The three processes are:

$$\begin{aligned}\log A_{c,t} &= t\log(1+\gamma_{AC}) + \log a_{c,t} \\ \log A_{h,t} &= t\log(1+\gamma_{AH}) + \log a_{h,t} \\ \log A_{k,t} &= t\log(1+\gamma_{AK}) + \log a_{k,t}\end{aligned}$$

so that $a_{c,t}$ denotes the stochastic stationary part of the consumption good shock, γ_{AC} the deterministic growth of the consumption good productivity and analogously for the two other productivities. The stochastic part of these processes follow:

$$\begin{aligned}\log a_{c,t} &= \rho_{AC} \log a_{c,t-1} + e_{c,t} \\ \log a_{h,t} &= \rho_{AH} \log a_{h,t-1} + e_{h,t} \\ \log a_{k,t} &= \rho_{AK} \log a_{k,t-1} + e_{k,t}\end{aligned}$$

It is useful to here note the relationship between the above technology trends and the implied trends for the real variables. Let G_c denote the deterministic trend in consumption. G_{IKc} and G_{IK_h} denotes the trend of investment in goods producing capital and house producing capital, respectively. G_{NH} denotes the trend growth of house production, and thereby the housing stock, and G_q is the trend in real house prices.

$$
\begin{aligned}
G_c &= G_{IK_h} = G_{NH}G_q = 1 + \gamma_{AC} + \frac{\mu_c}{1-\mu_c}\gamma_{AK} && (10)\\
G_{IK_c} &= 1 + \gamma_{AC} + \frac{1}{1-\mu_c}\gamma_{AK} && (11)\\
G_{NH} &= 1 + (\mu_h + \mu_o)\gamma_{AC} + \frac{\mu_c(\mu_h+\mu_o)}{1-\mu_c}\gamma_{AK} + (1-\mu_h-\mu_l-\mu_o)\gamma_{AH} && (12)\\
G_q &= 1 + (1-\mu_h-\mu_o)\gamma_{AC} + \frac{\mu_c(1-\mu_h-\mu_o)}{1-\mu_c}\gamma_{AK} - (1-\mu_h-\mu_l-\mu_o)\gamma_{AH} && (13)
\end{aligned}
$$

From the first equation we see that consumption, house producing capital and housing expenditure ($G_{NH}G_q$) grow at a rate determined jointly by goods productivity growth, γ_{AC}, and investment-specific productivity growth, γ_{AK}. The same terms affects the trend in residential investment G_{NH}, but scaled down to the degree, $(\mu_h + \mu_o)$, that non-housing technology affects housing.

Note how the last term in the equations for G_{NH} and G_q is identical except that it has opposite signs: house production is increasing in γ_{AH} while house prices are decreasing in the same parameter and by the same amount.

3 Estimation

3.1 Data

Our sample covers Sweden 1986q1-2008q3. We choose to start our sample period in 1986q1, as this is the first quarter where the official real estate price index is available, and coinciding roughly with the end of liberalization of bank regulations and financial regulations. A potential problem with our sample period is that monetary policy changed within the period: the fixed exchange rate regime collapsed in the 4th quarter of 1992 and the *de jure* inflation targeting regime was not instated until the 1st quarter of 1995. In spite of this gradual change in monetary policy we choose 1986 as the start of our time period so that the sample covers more than one house price cycle.

We use 10 dataseries for the estimation: Aggregate consumption (C), Business fixed investment (IK), Residential investment (NH), 4 quarter price inflation (π_4), Nominal short-term interest rate (R), Real house prices (q), Hours worked in consumption-good sector (N_c), Hours worked in housing sector (N_h), 4 quarter wage inflation in consumption-good sector (w_{c4}), 4 quarter wage inflation in the housing sector (w_{h4}). We have chosen 4 quarter differences for the three inflation series so as to reduce the impact of the substantial measurement error in these series, as well as to avoid the problems related to seasonal adjustment.[9] The data series used in the estimation are plotted in Figure 3.

[9] See Lindé (2003) for documentation of the problems with 1st difference inflation measurement in Swedish data, and how 4th difference inflation reduces the problem.

3.2 Calibrated parameters

The calibrated parameters are presented in Table A1. Most of these have been set to match ratios in the data, and overlap to a very large degree with the calibration in IN. A key parameter worth mentioning is the LTV ratio m which we set of 0.85. In Sweden for the sample period, 1986-2008, this ratio was plausibly increasing over time, but there is no high quality data available, in particular not on quarterly frequency, so we restrict the parameter to be constant.[10] Residential investment as a fraction of GDP was 3.4% for our sample period. Taking into account that our model only includes the private sector and that the value of residential investment as fraction of private sector GDP in our sample period is 6.3% we set $j = 0.11$ which yields $q * NH/GDP$ roughly equal to this number at the prior mode.

We set the steady state inflation target to 2% annually to coincide with the official stated target of Sveriges Riksbank.[11] β was set to yield a 2.25% annual real interest rate. The discount factor for the impatient households, β', was set substantially below β to ensure that the collateral constraint is always binding.

Based on results from initial estimations we calibrate all three indexation parameters to zero, so that they reflect absence of indexation.[12]

3.3 Priors

The priors are documented in Tables A2 and A3. As documented is these tables, the trend parameters and the shock standard deviations are scaled to obtain a prior standard deviation of similar order of magnitude as the other parameters. This is done for computational reasons to facilitate the optimization. For several parameters we use identical priors as IN. We follow IN by centering the prior for α at 0.65 but use a slightly less informative prior than they do with a standard deviation of 0.075.

For priors on the investment adjustment costs we follow Adolfson *et al.* (2005). Similarly we follow Adolfson *et al.* (2005) regarding the priors for the monetary policy parameters.

Apel, Friberg and Hallsten (2005) show using microlevel survey data that prices change roughly every year in Sweden. Accordingly, we center our prior for θ at 0.75. We set our prior for wage setting in the goods industry similarly. For the residential construction industry we use a less informative prior with a lower mean indicating more flexible wages to take into account more performance pay wage contracts and self-employed workers in the construction industry. We allow for the possibility of a limited labor movement between the two sectors by using less informative priors with high means for ξ and ξ', the curvature

[10] Also, see the discussion related to Liu, Wang and Zha (2009) below.

[11] In the matching of nominal variables between model and data we adjust for the fact that the model is set up for zero steady state inflation, while the data is assumed to have a steady state value of inflation equal to the inflation target of 2% annually.

[12] In exploratory estimations the posterior means of both ι_{wc} and ι_{π} where close to zero, and data appeared to contain no information on ι_{wh}.

of the disutility of working in a given sector.

Regarding the technology trends in housing, consumption goods and capital goods production we use data for a long period preceding our sample period, 1950-1985. We set the prior means for the three technology trends to match the trends in residential investment, business capital investment and consumption during this period.

We center all persistence parameters for shock processes at 0.8 and with a standard deviation of 0.075. For the standard deviations of shocks we use uninformative priors - inverse gamma distributions with two degrees of freedom. For each shock standard deviation we set the prior mode to roughly match the posterior median of IN.

We apply gamma distributed priors with low means for the measurement errors for three dataseries: w_{c4}, w_{h4} and NH. Both wage series are measured with substantial error, e.g. indicated by a recent data revision by Statistics Sweden more than 10 years back. The reason for allowing for measurement errors also in the residential construction hours is that we only have a proxy, in terms of total construction hours, for this variable.

4 Results

We obtained the estimation results using two random walk Metropolis-Hasting chains with 300 000 draws each after an appropriate burn-in and with an acceptance rate of 0.28. The prior-posterior plots and the Brooks-Gelman diagnostic plots for convergence are documented in the Computational Appendix. We estimate 19 structural parameters, 6 AR(1) coefficients, 9 standard deviations of shocks and 3 standard deviations of measurement errors. All results presented below refer to the posterior mean.

4.1 Parameter posterior distributions

The parameter posterior distributions are documented in Table A2 and the corresponding plots in the Computational Appendix. Below we discuss the most notable parameters.

The estimated productivity trend parameters imply the following annualized growth rates using (10-13): 1.8% for consumption, 3.3% for goods producing investment (and capital), -1.1% for residential investment (and housing stock) and 2.9% for real house prices. Note that a simple univariate linear trend estimated on the house prices series yields a very similar result, a 3.1% annualized growth rate. See Figure 4 for a plot of these dataseries and the corresponding estimated trends. These trends imply that consumption has been below trend for more than a decade and that real house prices are above trend since 2003.

The fraction of collateral constrained households, $1-\alpha$, is estimated to be 1/5. The sectorial labor mobility is estimated to be very low, corresponding to high values of ξ and ξ' around 5. As a contrast investment adjustment costs, S_c'', and variable capital adjustment costs, ζ, are estimated to be low. At a posterior mean of $\theta_{wc} = 0.95$ the Calvo wage parameter for the consumption good sector indicate very rigid wages, while the housing sector wages are quite flexible with $\theta_{wh} = 0.3$.

The estimated measurement error for housing sectors hours N_h is small, while the measurement errors for both wage series are substantial. This is most clear in Figure 3 where the smoothed variables (not incorporating measurement errors) are plotted against the data.[13]

We found that data is informative about all parameters except three: The Frisch elasticity for impatient households, η', the investment adjustment cost curvature for capital used in housing production, S''_h, and the Taylor rule parameter for responding to inflation, r_π. For these parameters the posterior accordingly approximately coincides with the prior.

Comparing the estimation results to IN we note that labor mobility between the housing and the non-housing good sector, not surprisingly, is substantially lower in Sweden than in the US. Another interesting contrast to their results is that we find housing sector wages to be more flexible than non-housing sector wages. Our estimate of the Taylor rule parameter $r_{\Delta y} = 0.15$ is between their higher estimate and lower values in most of the literature (Smets and Wouters, 2007, and Adolfson *et al.*, 2005) Finally, in contrast to IN our estimate of housing sector productivity γ_{AH} is so negative that it offsets the positive effect of other productivity trends on residential investment G_{NH}. We therefore get a negative estimate of G_{NH} and accordingly (see equations (10)-(13)) house prices grow faster than consumption, $G_q > G_c$. Other methods also indicate negative change in the productivity in the housing sector during our sample period, see Boverket (2002), similar to what Corrado *et al.* (2007) report for the U.S. An alternative possible reason for the observed downward trend in residential investment and upward trend in house prices - interpreted as a negative technology trend - is the decrease in government subsidies and increase in taxes on residential investment that occurred in our sample period, see section 1.1. Outside the model, a second alternative explanation for the perceived decrease in productivity is that it reflects an upward trend in the price of the key input in residential production - land. The data quality on the available time series for residential land prices is limited, mainly because only price data for land used in new construction is observed which leads to downward bias due to sample selection problems of the type emphasized by Davis and Heathcote (2007).[14] Nevertheless, the land price and construction cost data indicates that i) land costs as a fraction of the cost of new houses is not increasing over the sample period, and ii) the

[13]We have confirmed that the posterior means are only very marginally affected by removing the badly measured housing sector wages w_{h4} from the observables, and for calibrating the measurement error for w_{c4} to 0.01, i.e. half its estimated value.

[14]The land price and construction cost data is from Statistics Sweden, SCB (2010), p. 134 and SCB online. The potential selection problem is that land with new residential construction plausibly are in less attractive areas - with different land price dynamics - than the existing housing stock. Davis and Heathcote (2007) apply a method to circumvent this data selection problem for the U.S, using quarterly data for the period 1975-2006. They view a house as a bundle of land and a structure and then compute the price of land residually using the price of structures (construction) and house prices. They conclude that land prices are the main driver of house price movements, both in terms of long-term trends and in terms of fluctuations of the business cycle.

upward trend in land prices account for at most half of the trend increase in house prices, and even less of the actual (cyclical+trend) increase.

4.2 Impulse response functions

The impulse response functions (IRF) for a monetary policy shock at the posterior mean is displayed in Figure 5. In this subsection we analyze the estimated benchmark results, shown in the figures using a solid line. An 80 annualized basis points (ABP) temporary increase in the interest rate yield an initial decrease in inflation of 50 ABP and a hump-shaped decrease in GDP and business investment of roughly 1% and 2%, respectively. Residential investment and house prices both decrease by roughly 1%, although house prices recover by half within a year. The consumption of impatient (collateral constrained) households jumps down initially and decreases by a factor 4 more than for patient households. This is because the collateral constraint becomes tighter for the impatient households both because of the fall in house prices and because of the Fisher debt-deflation effect induced by the surprise fall in inflation. Such a fall implies higher ex-post real value of debt and therefore a wealth transfer from borrowers to savers.

Compared to the monetary policy IRFs in IN the main difference is that we get the hump-shaped response in business investment, and thereby GDP, that we intended by introducing investment adjustment costs. Also more generally, for other shocks, our model specification generates more persistent, perhaps more realistic, responses of the variables of interest.

The IRF for a housing preference shock, e_j, is displayed in Figure 6. Note that this shock is highly persistent with an AR(1) coefficient of 0.97 so that - in contrast to the monetary policy shock - a lot of the persistence is external. The increase in housing demand leads to an immediate increase in house prices and residential investment, as well as consumption of impatient households due to the relaxed collateral constraint. When we compare to the U.S. results of IN the main difference is that in Sweden house prices, and therefore consumption, respond more to this shock, while residential investment respond less. This is in line with a general view of Swedish residential investment as non-responsive and sluggish. Furthermore, in contrast to IN we get a positive response of business investment at the impact of the shock.

In Figure 7 we illustrate the IRF of a shock to consumption good technology, e_c. This IRF is quite conventional and implies an initial decrease in inflation and the interest rate, and an increase in business investment and aggregate consumption. Interestingly, residential investment initially decrease although house prices increase on impact.

4.3 Quantitative importance of collateral constraints

We now compare the impulse responses across model specifications, keeping the estimated parameters fixed at the posterior mean values. This implies that we keep the fraction of collateral constrained households fixed, which might be a debatable assumption. The results for the monetary policy shock are summarized in Table 2 and the dynamics are plotted separately in the same figure as for the baseline monetary policy IRF, Figure 5. The dotted line shows the dynamics of a model without collateral constraints. In that model, aggregate variables respond less to a monetary policy shock. Comparing the maximum deviation from steady state we note that the collateral effect contributes to the response of inflation by 8%, to GDP by 9% and to aggregate consumption by 26%. The first row of Table 2 summarize these results.

	π	GDP	C
Fraction from collateral constraint	8.3	9.2	26.0
Increase if LTV 85% → 95%	3.5	8.3	24.0

Table 2. Effect of collateral constraint on monetary transmission, as a fraction of total monetary transmission.

The dashed line in Figure 5 and the second row of Table 2 illustrates the dynamics if the maximum LTV, m, is set to 0.95 instead of our benchmark 0.85 (in other words, if the down-payment requirement decreases from 15% to 5%), similarly to what happened in the most recent decade in Sweden and many other countries.[15] With the higher LTV the impatient households are more heavily indebted and are forced to reduce their consumption twice as much initially. Their housing demand also falls more, and residential investment therefore decreases more. This contrasts with the result in Aoki *et al.* (2004) where improved credit market access lead to smaller effects of monetary policy on residential investment.[16] General equilibrium effects makes business investment and consumption of patient household decrease more as well, but the additional effect on inflation is small, 3.5%. The maximum deviation from steady state of GDP is 8% larger and for aggregate consumption 24% larger. Comparing the two rows in Table 2 we note that when LTV is increased from 85% to 95% the size of the collateral effect on the response of π increase by roughly 40%, and of GDP and consumption by roughly 90%. Calza, Monacelli and Stracca (2007) showed qualitatively that an increased LTV implies more shock amplification and we are here able to quantify it. Because it runs counter to some people's preconceptions it is important to point out that financial development that increases households' access to finance in this way amplify the effects of some demand shocks, mainly monetary policy shocks and housing demand shocks (see below).

[15]Note that the analysis does not include transition dynamics between the different steady states, but merely the dynamics around the corresponding steady state.

[16]The key difference in financial friction modelling between our approach and Aoki *et al.* (2004) is that they use costly state verification while we rely on collateral constraints motivated by limited contract enforceability.

Switching to the housing preference shock plotted in Figure 6 and comparing the benchmark model to the specification without collateral constraints we note the importance of the collateral effect for this shock: all the expansionary effect of the housing demand shock on inflation and consumption comes from the collateral effect.

Comparing the dashed line, illustrating $m = 0.95$, to the benchmark also shows huge differences: The impact of the shock more than doubles for aggregate macro variables (i.e. not including NH and q). This points to the increased importance of housing shocks in recent years, and more generally, to the importance of fully understanding what determines the LTV over time.

The IRF of a shock to consumption good technology displays almost no differences across specifications - the effects of this shock are not amplified by the existence of the collateral constraint or the level of the LTV. The same is true for most other shocks (not plotted): the effects of the collateral constraints are either zero or dampening. The reason is that only shocks that move real house prices and goods inflation in the same direction generate large collateral effects because only then do the house price capital gains and the Fisher debt-deflation mechanism affect the borrower balance sheet in the same direction.

4.4 Variance decomposition

In Table A4 we present the variance decomposition for 1, 8 and 20 quarter forecast horizons respectively. We start by discussing the 8 quarter horizon. The first thing to note is the, from a shock perspective, large degree of macro-housing disconnect: the housing technology shock, e_h, accounts for 3/4 of the variance in residential investment and the housing demand shock, e_j, for 3/4 of the variance in house prices. At the same time neither one of these two shocks contribute much to macro variation - less than 1% of variance of GDP and aggregate consumption each, and nothing of the variance in inflation. For macro variables instead the technology shocks e_c and e_k are generally important. The most important shocks for GDP is the monetary policy shock, e_r, and the investment-specific technology shock, e_k. The monetary policy shock is also unusually central for the other variables of interest. For inflation, the cost-push shock e_p dominates followed by the inflation target shock e_s. Given the shift in monetary policy during the sample period it is not surprising that the inflation target shock is important for inflation and dominates on longer horizons. For aggregate consumption the time preference shock e_z is the most important.

The "traditional" macro shocks of course have some importance for housing variables: House prices are to a substantial degree affected by the neutral technology shock e_c and the monetary policy shock e_r. For residential investment instead e_r and the labor supply shock, e_τ, matter.

Comparing the 1 quarter horizon to the 8 quarters horizon, the two housing shocks are substantially more important for GDP and consumption at the shorter horizon. The monetary policy shock is also more important, both for house prices and macro variables, while technology shocks matter less. Finally, we note that the importance of the shocks for each variable generally, but not always, vary monotonically with the horizon, and we therefore refrain from commenting the results for the 20 quarters horizon.

4.5 Historical shocks and shock decomposition

The smoothed values of the shock processes are displayed in Figure 8. In line with the variance decomposition it seems that construction sector productivity a_h follows the dataseries for residential investment while the housing preference shock process j more closely follows the house price series. Part of the decrease of construction sector productivity in the early 1990's might consist of the changed tax treatment (VAT on building materials) mentioned in section 1.1. Similarly, some part of the decrease in construction sector productivity at the very end of the sample is probably due to the decrease in construction subsidies that took place then. The housing preference shock tends to soak up any change in housing demand, including those caused by changed taxation of house owners, e.g. limitations on interest rate deductions around 1991 and the decreased/abolished residential property tax announced in 2006-2007. Liu, Wang and Zha (2009) show that an effect equivalent in the aggregate to a housing preference shock can be generated by variation over time in the maximum LTV parameter, m. Using that interpretation the low frequency upward movement of the housing preference shock j since 1996 reflects increased availability of mortgage credit. This interpretation coincides with casual observation of banks' lending behavior, both in the recent housing price boom and in the boom-bust around 1990.

The model interprets monetary policy as following an inflation target that decreases stepwise until 2006, although mainly in 1992-1993. The defense of the fixed exchange rate regime in 1992 is interpreted as a couple of large contractionary monetary policy shocks.

In Figure 9 we present the historical shock decomposition for real house prices, q, in terms of deviation from trend. The large and negative contribution from monetary policy shocks, e_r, to real house prices, q, 1990-2004 points to the very long-lived effects of monetary policy in this model on both housing variables. This characteristic is also evident from the monetary policy impulse response function discussed above. Since 2005 monetary policy shocks have contributed somewhat to the high level of q. We note that the housing demand shock e_j had positive contribution to q around 1990, negative contribution 1994-2003 and was an important reason for q being above trend 2004-2007. The negative housing technology shock e_h have had positive impact on q since 1994, but this has been partially offset by the consumption technology shocks, e_c.

Shock decomposition for aggregate consumption is documented in Figure 10. The main point we want to illustrate here is that shocks to the housing sector have not been important for consumption, consistent with the variance decomposition. In spite of the unprecedented house price rally towards the end of the sample the contribution of housing demand shocks is small. Instead we note that monetary policy shocks depressed consumption until 2005 and then had an expansionary effect.

4.6 Validation

4.6.1 Business cycle moments

Table A5 contains the key business cycle moments both for the data and the model, both HP-filtered. Let us start by pointing out that the data moments are broadly similar to what was documented for the U.S. by IN and other authors. The main differences are that in Sweden business investment, IK, and house prices, q, are more volatile and residential investment, NH, and GDP less correlated.

Our estimated model does a good job in terms of the standard deviation of key variables, except that it overpredicts the volatility of aggregate consumption, C. The autocorrelations implied by the model are also roughly in line with the data, with the most notable discrepancy being the underprediction of the autocorrelation of NH, and q.

Regarding the correlations the model does fine except in one dimension: There are large underpredictions of the correlations between q and the real quantities GDP, C, and NH. This might indicate that there is less of a disconnect between macro and housing variables than implied by the model. Alternatively, the HP-filtering removes too much of the medium frequency variation in the data, which is different between these four time series, and thereby overstate their comovement.

4.6.2 Forecast performance

Another way to evaluate the empirical performance of a DSGE model is to look at its forecast performance. We focus our attention on the real house price q. For that purpose we re-estimate the model on the first half of the sample, i.e. 1986q1-1997q1, and do out-of-sample forecast evaluation. We also generate in-sample forecasts using the model estimated on the full sample. The in-sample forecasts from each quarter 1988q3 and onwards are plotted in Figure 11.[17] The estimated positive trend in house prices generate increasing forecast paths, except for the last quarters of the sample where decreasing forecast paths for q obtain as the house prices have moved far above trend. The recent turning point / slow down in house prices was predicted to happen long before it actually took place. In other words, the model gets the timing of the turning point wrong, but the underlying tendency right.

In Table A6 we document the root mean square error (RMSE) for the real house price

[17] The subsample estimation generate qualitatively similar forecasts (not plotted here). The most striking difference is that the estimated house price trend is lower for the subsample estimation, and long term forecasts therefore tend towards lower levels.

For the in-sample forecasts the starting point 1988q3 implies 10 periods of initial model filtering before forecasts start.

forecast, for 1 to 12 quarters forecast horizon both in-sample and out-of-sample. For comparison purposes we also report the RMSE of a deterministic linear trend, allowing for a constant term in the linear regression, estimated on the corresponding sample period. The in-sample DSGE model forecasts have a lower RMSE than the trend on horizons of 8 quarters and longer, and similar RMSE on short horizons. The subsample estimation out-of-sample forecasts dominate the trend on all horizons. One the whole the DSGE model forecasts are at least as good as the linear trend, and this is a reasonably high standard for this type of time series and model.[18]

5 Concluding remarks

5.1 Limitations

The fact that we model a closed economy while Sweden has substantial international interactions clearly is a rough approximation. Nevertheless we think our results are robust to this simplifying assumption, and that the benefits of not complicating the model further outweigh the costs.[19] Similarly we do not think it is beneficial to attempt to explicitly model the various tax and residential construction subsidy changes that have occurred during the sample period. A final simplification is that the model does not allow for rental housing, while roughly half of households rent their housing in Sweden.[20] Incorporating the heavily regulated Swedish housing rental market in this type of model is beyond the scope of the paper. As mentioned above in section 1.1.1, due to rent control it is hard to find an apartment to rent, so the assumption of no rented housing is approximately true for new households.

5.2 Main results and conclusions

We developed and estimated a DSGE model with two sectors and a role for housing as collateral. The main results of the estimated model are:

i) A fifth of the population appear to be collateral constrained, and this implies that house prices have substantial effects on key macro variables, in addition to the effect that would occur in a model where there is no collateral role for housing.

ii) Housing used as collateral for loans reinforces the effects of monetary policy. In the presence of nominal loan contracts this mechanism functions both through the effects of the interest rate on house prices, i.e. the collateral value, as well as on inflation and thereby the

[18] The relative forecast performance of the DSGE model for inflation, the nominal interest rate, consumption and business investment is also as good as a linear trend (or a random walk for non-trending variables).

[19] See Christensen, Corrigan, Mendicino and Nishiyama (2009) for an example of an open economy model with housing collateral.

[20] The share of owner-occupied housing was 55% in 2005, with 38% owner-occupied houses and 17% owner-occupied apartments (Hüfner and Lundsgaard (2007)). The former share has been roughly constant since 1980, while the latter share has been increasing slightly over time as rental apartments have been converted into owner-occupied apartments.

real value of nominal debt. 8% of the effect of a monetary policy shock on inflation is due to collateral constraints, and the corresponding numbers are 9% for GDP and 26% for consumption, respectively. This component of the monetary transmission mechanism becomes stronger the higher the loan-to-value is. When the LTV is increased from 85% to 95% the size of the collateral effect, which is a component of the monetary transmission mechanism, on the response of inflation increase by roughly 40%, and of GDP and consumption by roughly 90%.

iii) An increased LTV also makes housing preference shocks more powerful: their effects on most macroeconomic variables more than doubles. But, for most other shocks the quantitative importance of collateral constraints are limited, as only shocks that move house prices and inflation in the same direction generate large collateral effects. Only for such shocks do the house price capital gains and the Fisher debt-deflation mechanism affect the borrower balance sheet in the same direction.

iv) Shocks to the demand for or supply of housing explain only a very small fraction, less than 2%, of the fluctuations in GDP and inflation. On the other hand, house prices are explained by macroeconomic shocks to a higher degree, roughly 25%.

We draw two main conclusions from these results: To properly understand the monetary transmission mechanism and its changing nature over time, we need to take into account the effects of housing related collateral constraints. The fact that loan-to-value ratios, or more broadly, household indebtedness, has increased substantially in the last decade implies substantial amplification of some shocks on both housing and the macroeconomy more generally. On the other hand, our results indicate that there is no need to worry about macroeconomic implications of shocks originating in the housing market, as these implications are almost negligible quantitatively.

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A Appendix

A.1 Tables and Figures

Parameter	Description	Value
β	subjective discount factor, patient hhs	0.994375
β'	subjective discount factor, impatient hhs	0.97
j	steady state utility weight on housing	0.11
μ_c	capital share, consumption sector	0.35
μ_h	capital share, housing sector	0.10
μ_l	land share, housing sector	0.10
μ_o	intermediate good share, housing sector	0.10
δ_h	housing depreciation	0.01
δ_{kc}	capital depreciation, consumption sector	0.025
δ_{kh}	capital depreciation, housing sector	0.03
X	steady state price markup	1.15
X_{wc}	steady state wage markup, consumption sector	1.15
X_{wh}	steady state wage markup, housing sector	1.15
m	loan-to-value ratio	0.85
$\rho_{\bar{\pi}}$	AR(1) coefficient, inflation target	0.975

Table A1. Calibrated parameters.

	Prior	Prior mean	Prior s.d.	Post. mean	Post. s.d.	5 %	95 %
$\gamma_{AC}100$	N	0.450	0.200	0.231	0.047	0.157	0.309
$\gamma_{AH}100$	N	0.200	0.200	-0.519	0.137	-0.745	-0.296
$\gamma_{AK}100$	N	0.250	0.200	0.385	0.052	0.302	0.471
ε	β	0.500	0.075	0.546	0.058	0.453	0.643
ε'	β	0.500	0.075	0.547	0.078	0.419	0.678
η	Γ	0.500	0.100	0.577	0.112	0.394	0.760
η'	Γ	0.500	0.100	0.511	0.102	0.343	0.675
ξ	Γ	4.000	1.000	5.310	0.670	4.218	6.341
ξ'	Γ	4.000	1.000	4.532	1.133	2.699	6.360
S_c''	N	7.700	1.500	5.316	1.417	3.009	7.638
S_h''	N	7.700	1.500	7.485	1.494	5.055	9.956
α	β	0.650	0.075	0.820	0.044	0.749	0.892
ρ_R	β	0.800	0.050	0.849	0.020	0.816	0.883
r_π	N	1.700	0.100	1.700	0.097	1.541	1.858
$r_{\Delta y}$	N	0.063	0.050	0.148	0.022	0.111	0.184
θ	β	0.750	0.075	0.806	0.036	0.749	0.866
θ_{wc}	β	0.750	0.075	0.951	0.009	0.937	0.967
θ_{wh}	β	0.600	0.100	0.295	0.053	0.207	0.383
ζ	β	0.500	0.200	0.173	0.099	0.024	0.319
ρ_{AC}	β	0.800	0.075	0.946	0.022	0.914	0.981
ρ_{AH}	β	0.800	0.075	0.968	0.008	0.956	0.981
ρ_{AK}	β	0.800	0.075	0.676	0.059	0.581	0.774
ρ_j	β	0.800	0.075	0.966	0.011	0.948	0.984
ρ_z	β	0.800	0.075	0.808	0.048	0.733	0.885
ρ_τ	β	0.800	0.075	0.865	0.034	0.811	0.919

Table A2. Prior and posterior parameter values.

	Prior	Prior mean	Prior d.f./s.d.	Post. mean	Post. s.d.	5 %	95 %
$e_c 100$	inv-Γ	4.0	2	1.716	0.141	1.483	1.939
$e_r 1000$	inv-Γ	5.0	2	3.483	0.327	2.952	4.005
$e_h 100$	inv-Γ	4.0	2	4.811	0.391	4.177	5.447
$e_j 10$	inv-Γ	0.7	2	1.303	0.378	0.694	1.870
$e_k 100$	inv-Γ	4.0	2	5.843	1.513	3.390	8.264
$e_p 1000$	inv-Γ	5.0	2	5.504	0.500	4.674	6.290
$e_s 1000$	inv-Γ	1.0	2	1.870	0.347	1.324	2.426
$e_\tau 10$	inv-Γ	0.6	2	0.918	0.185	0.615	1.208
$e_z 100$	inv-Γ	4.0	2	3.035	0.550	2.164	3.873
$ME(N_h)1000$	Γ	1.0	10	20	3.0	15.3	25.0
$ME(w_{h4})1000$	Γ	1.0	10	171	12.7	149.4	190.6
$ME(w_{c4})1000$	Γ	1.0	10	20	1.8	17.1	22.9

Table A3. Prior and posterior standard deviations of shocks.

	e_c	e_r	e_h	e_j	e_k	e_p	e_s	e_τ	e_z
1 quarter									
Interest rate	1.0	59.7	1.1	0.9	8.7	9.7	6.4	0.1	12.3
Inflation	14.1	5.3	0.0	0.0	0.1	70.1	8.9	0.9	0.6
GDP	1.9	37.7	3.1	2.1	19.3	2.9	7.7	1.5	23.9
Business Investment	1.6	10.5	0.0	0.0	84.8	0.9	2.0	0.1	0.1
Residential Investment	1.5	4.1	79.5	5.7	0.1	0.2	0.6	8.2	0.1
House Prices	1.0	19.0	3.5	68.1	2.1	2.6	2.7	0.0	1.1
Aggr. Consumption	2.2	31.0	0.6	1.3	1.0	2.3	6.8	0.2	54.8
Consumption, patient	2.9	19.1	0.2	0.0	1.4	1.9	4.3	0.2	69.9
Consumption, impatient	0.1	56.6	2.1	21	0.0	2.2	11.9	0.0	6.0
8 quarters									
Interest rate	1.2	15.5	0.4	0.7	31.1	2.4	30.8	0.0	18
Inflation	15.5	10.1	0.0	0.0	1.5	39.3	29.9	1.7	2.0
GDP	12.5	31.2	0.6	0.7	28.7	1.2	10.2	2.9	12
Business Investment	9.7	17.3	0.0	0.0	65.5	0.7	5.3	1.3	0.0
Residential Investment	0.5	5.3	77.9	4.9	2.1	0.2	1.5	7.4	0.4
House Prices	4.2	9.5	4.0	77.7	1.0	0.8	2.1	0.2	0.6
Aggr. Consumption	10.4	29.7	0.4	0.8	1.2	1.2	10.2	1.7	44.3
Consumption, patient	12.3	18.8	0.2	0.0	0.9	0.9	7.4	1.8	57.7
Consumption, impatient	2.7	57.4	1.1	11.5	4.5	2.0	15.3	0.7	4.9
20 quarters									
Interest rate	1.4	11.2	0.3	0.5	24.2	1.6	48.4	0.2	12.2
Inflation	12.2	9.4	0.0	0.0	2.3	29.1	43.7	1.4	1.9
GDP	21.7	25.3	0.7	0.6	23.5	0.6	14.8	6.4	6.5
Business Investment	20.3	18.9	0.0	0.2	44	0.4	10.9	4.9	0.4
Residential Investment	0.8	5.0	76.9	5.2	2.7	0.1	2.7	6.3	0.4
House Prices	6.5	7.1	4.9	74.6	2.6	0.5	2.8	0.8	0.3
Aggr. Consumption	18.9	25.3	0.2	0.5	9.0	0.7	14.8	4.8	25.8
Consumption, patient	20.5	18.5	0.2	0.2	8.1	0.5	12.8	4.9	34.4
Consumption, impatient	10.5	44.7	0.8	6.9	11.2	1.3	17.8	3.3	3.5

Table A4. Variance decomposition. 1, 8 and 20 quarters horizon respectively.

	Data	Model	Data	Model
	Std.dev (%)		Autocorr	
GDP	2.25	2.73	0.89	0.89
C	1.31	2.44	0.71	0.86
IK	7.22	6.46	0.94	0.92
NH	9.33	6.75	0.93	0.69
q	4.31	3.95	0.90	0.70
	Correlation			
GDP, C	0.86	0.71		
GDP, IK	0.82	0.79		
GDP, NH	0.46	0.35		
GDP, q	0.82	0.21		
q, C	0.62	0.30		
q, NH	0.47	0.10		
IK, NH	0.01	0.18		
C, NH	0.34	0.14		

Table A5. Business Cycle Moments. Detrended using a Hodrick-Prescott filter with $\lambda = 1600$.

	Out-of-sample 1997q2-		In-sample 1988q3-	
Horizon	DSGE	Linear trend	DSGE	Linear trend
1	0.025	0.025	0.027	0.024
2	0.043	0.044	0.046	0.041
3	0.060	0.063	0.062	0.057
4	0.077	0.081	0.077	0.071
5	0.094	0.10	0.091	0.087
6	0.11	0.12	0.10	0.10
7	0.12	0.14	0.11	0.11
8	0.14	0.16	0.12	0.13
9	0.14	0.18	0.13	0.14
10	0.16	0.20	0.14	0.15
11	0.17	0.22	0.15	0.16
12	0.18	0.23	0.15	0.18

Table A6. Root mean square error for log real house price, q, forecasts.

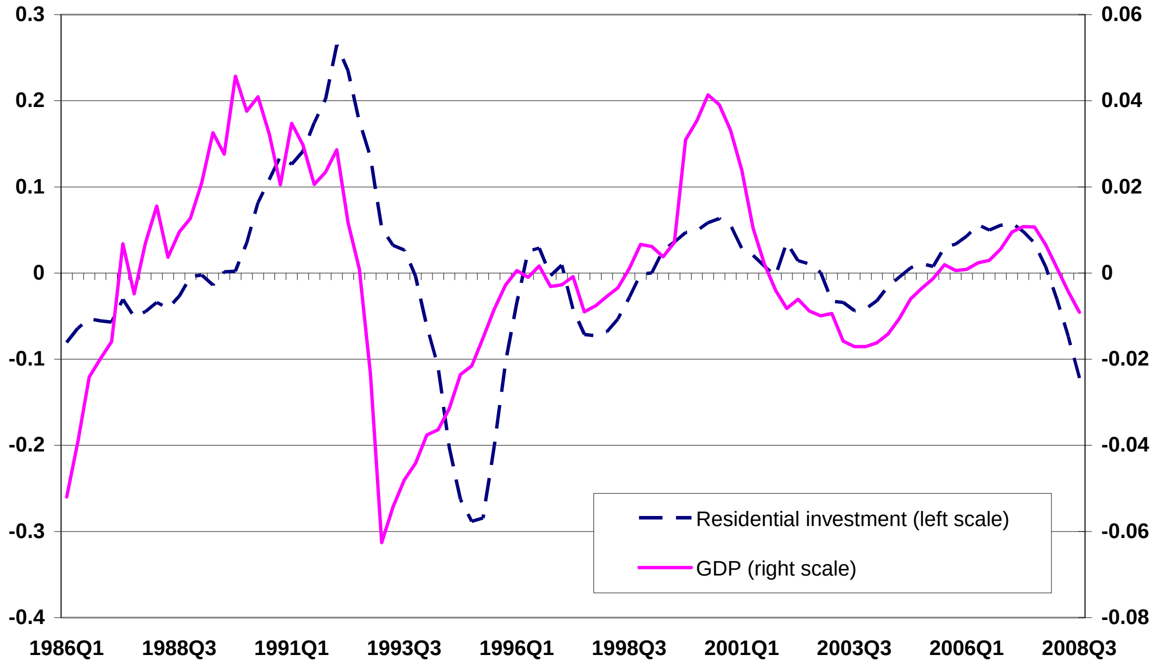

Figure 1. Real residential investment and real GDP detrended using a Hodrick-Prescott filter with $\lambda = 1600$.

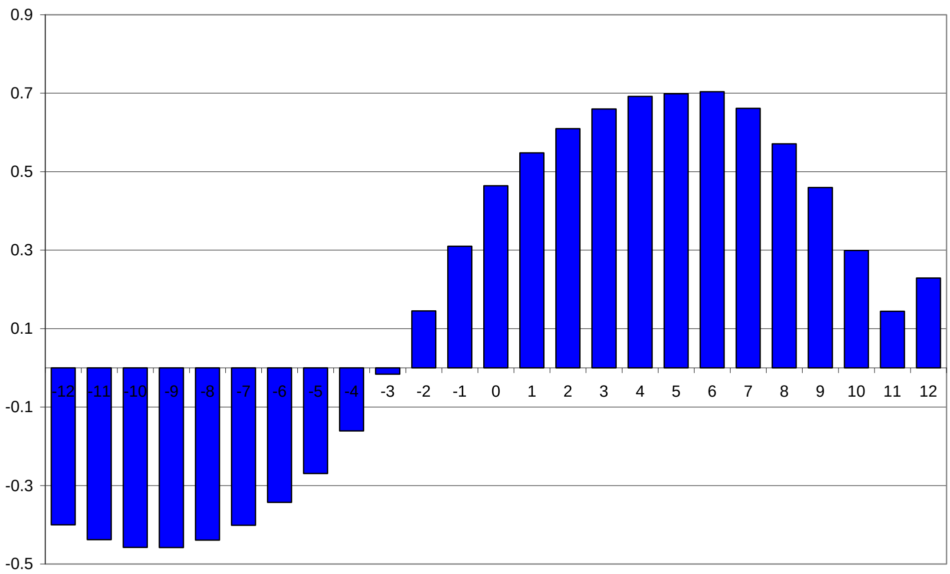

Figure 2. Cross correlation of real residential investment with the output gap (quarters by which residential investment lag the output gap).

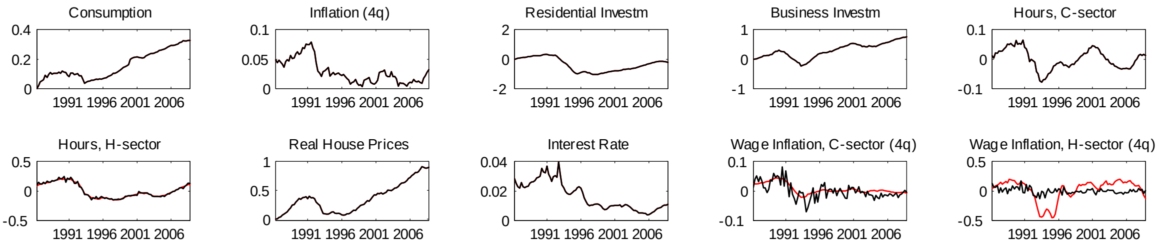

Figure 3. Matched data series (black) and smoothed variables (red), 1986q1-2008q3.

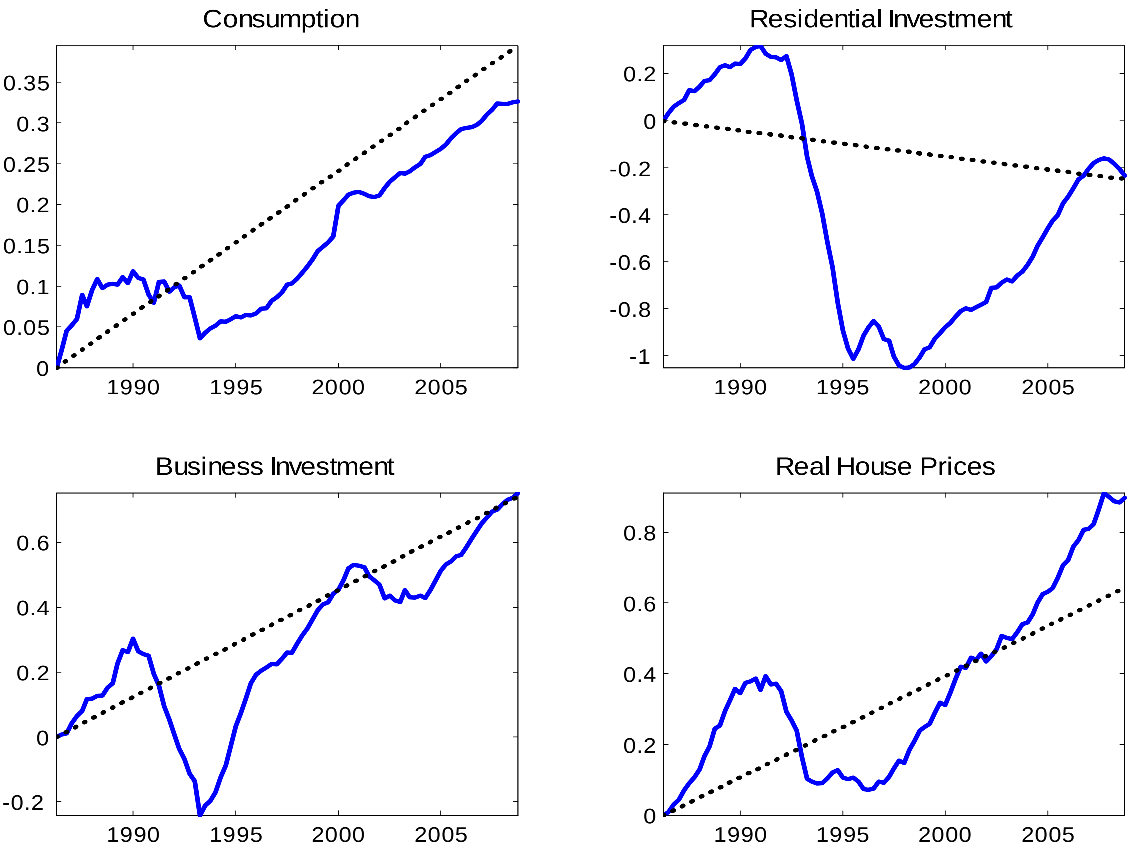

Figure 4. Selected data series 1986q1-2008q3 and estimated trends.

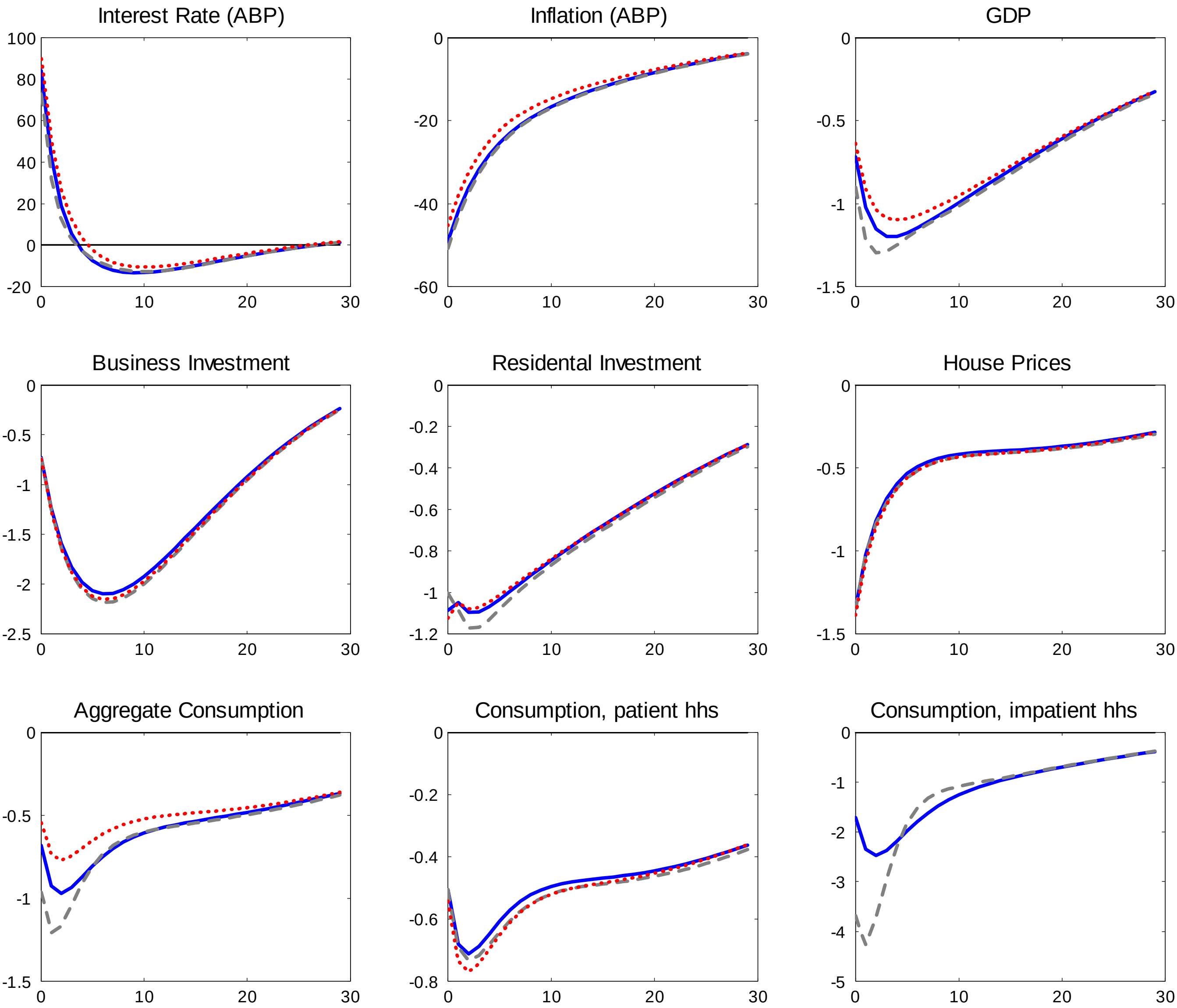

Figure 5. Impulse response functions to a monetary policy shock, $e_{r,t}$. Interest rate and inflation in annualized basis points (ABP), all other variables in percent deviation from steady state. Solid line shows benchmark calibration loan-to-value ratio $M = 0.85$, dashed line shows $M = 0.95$ and dotted line shows model without collateral constraints.

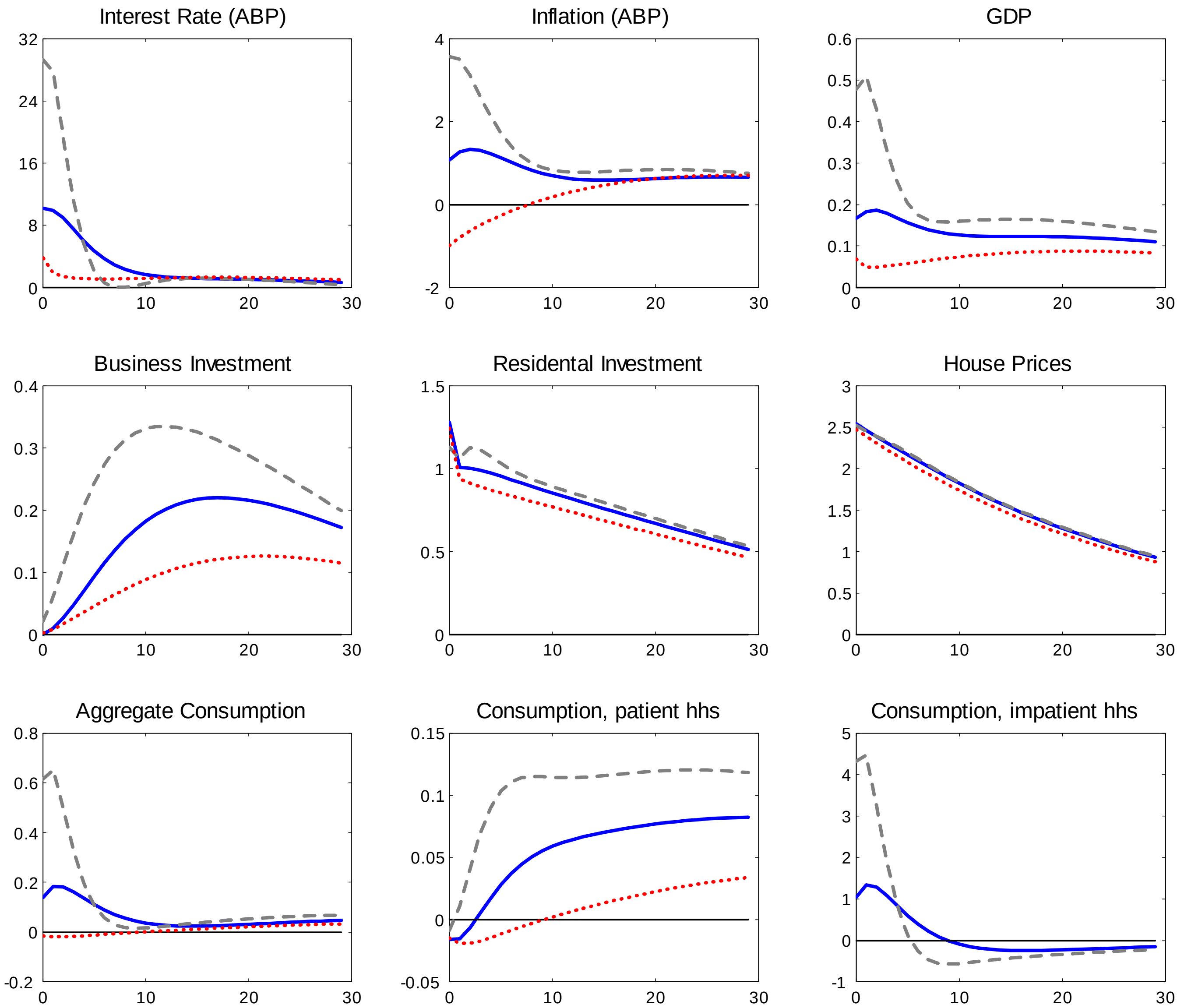

Figure 6. Impulse response functions to a housing preference shock, $e_{j,t}$. Plotting and scale details as in Figure 5.

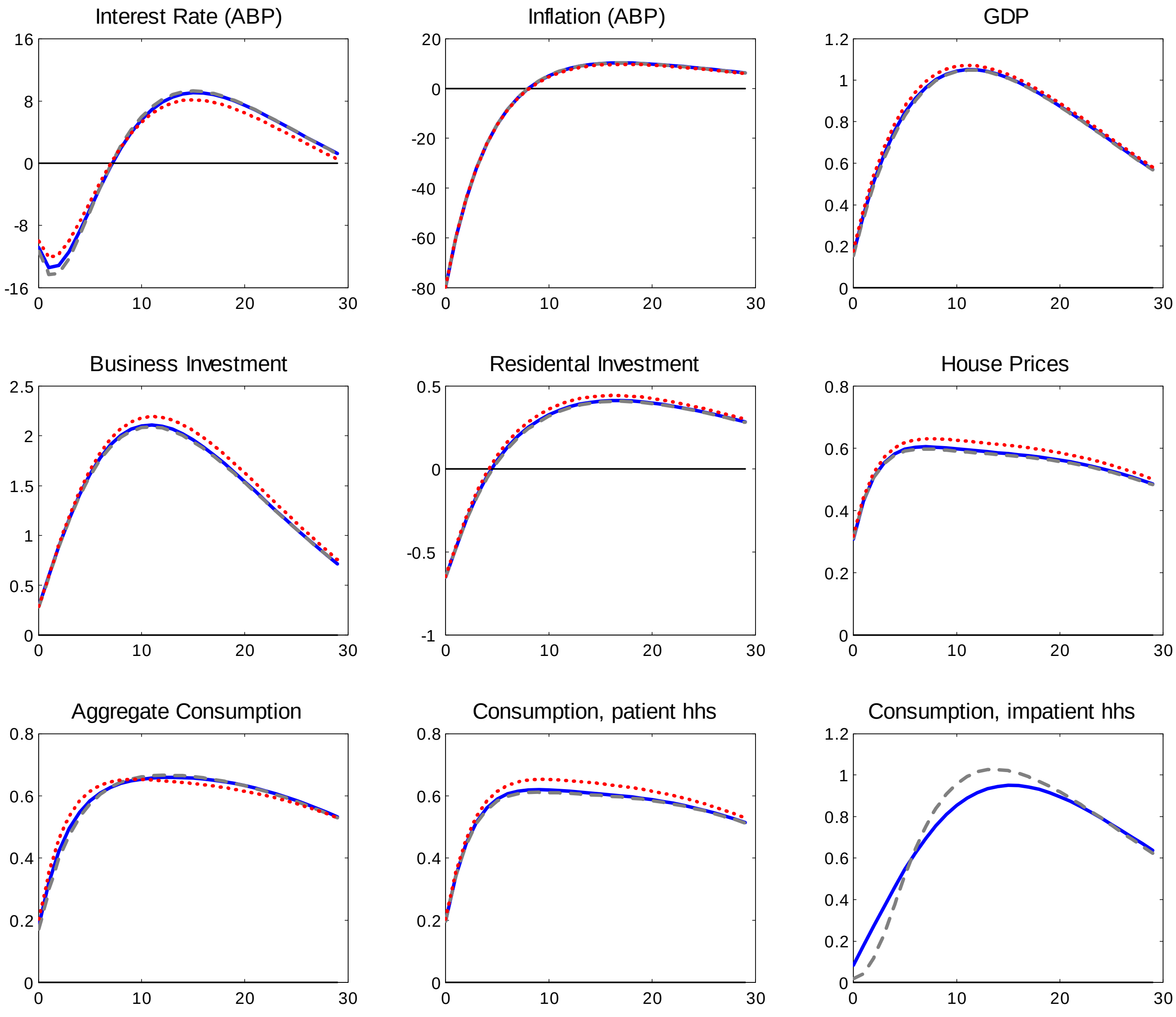

Figure 7. Impulse response functions to a consumption good technology shock, $e_{c,t}$. Plotting and scale details as in Figure 5.

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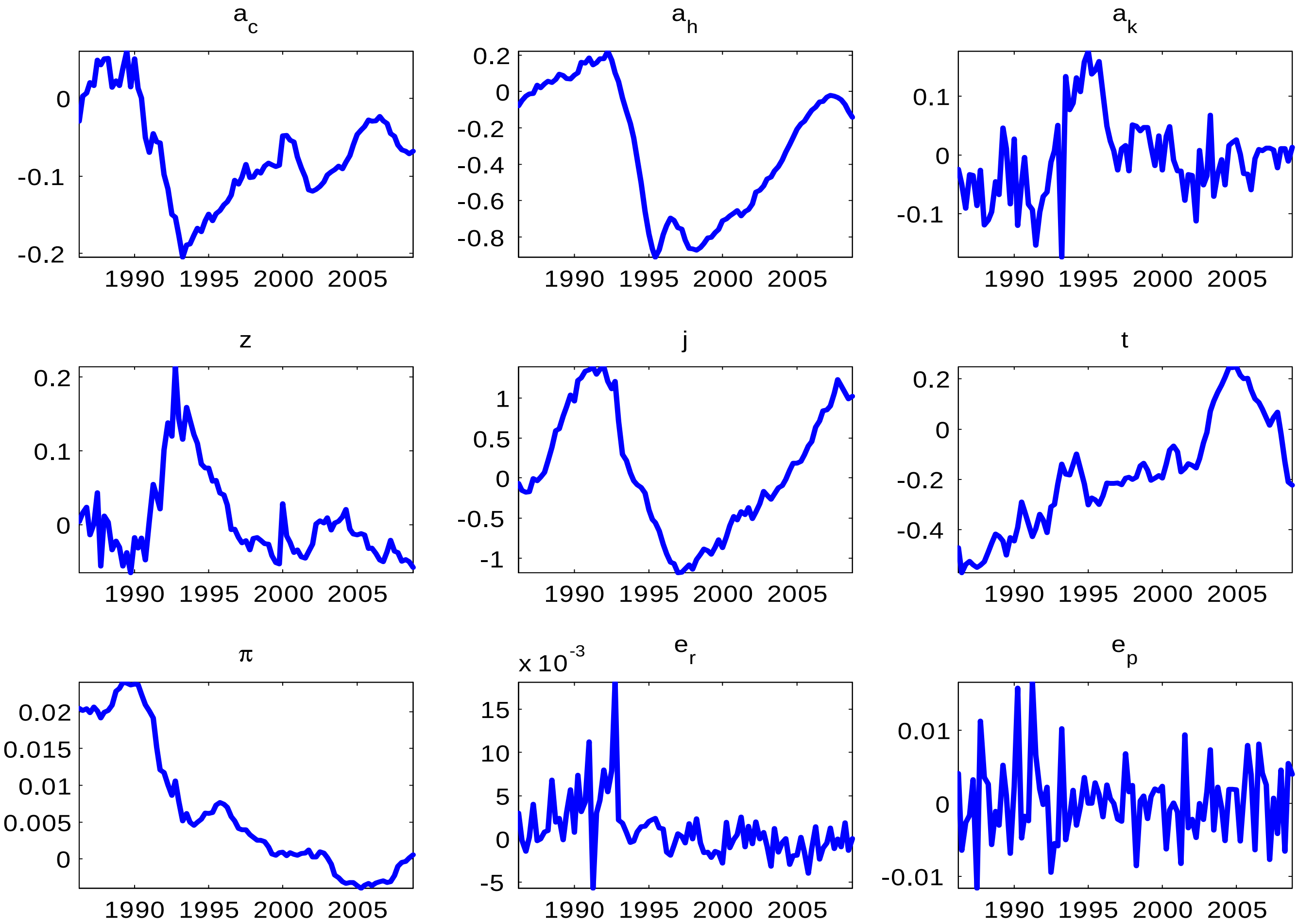

Figure 8. Smoothed exogenous shock processes.

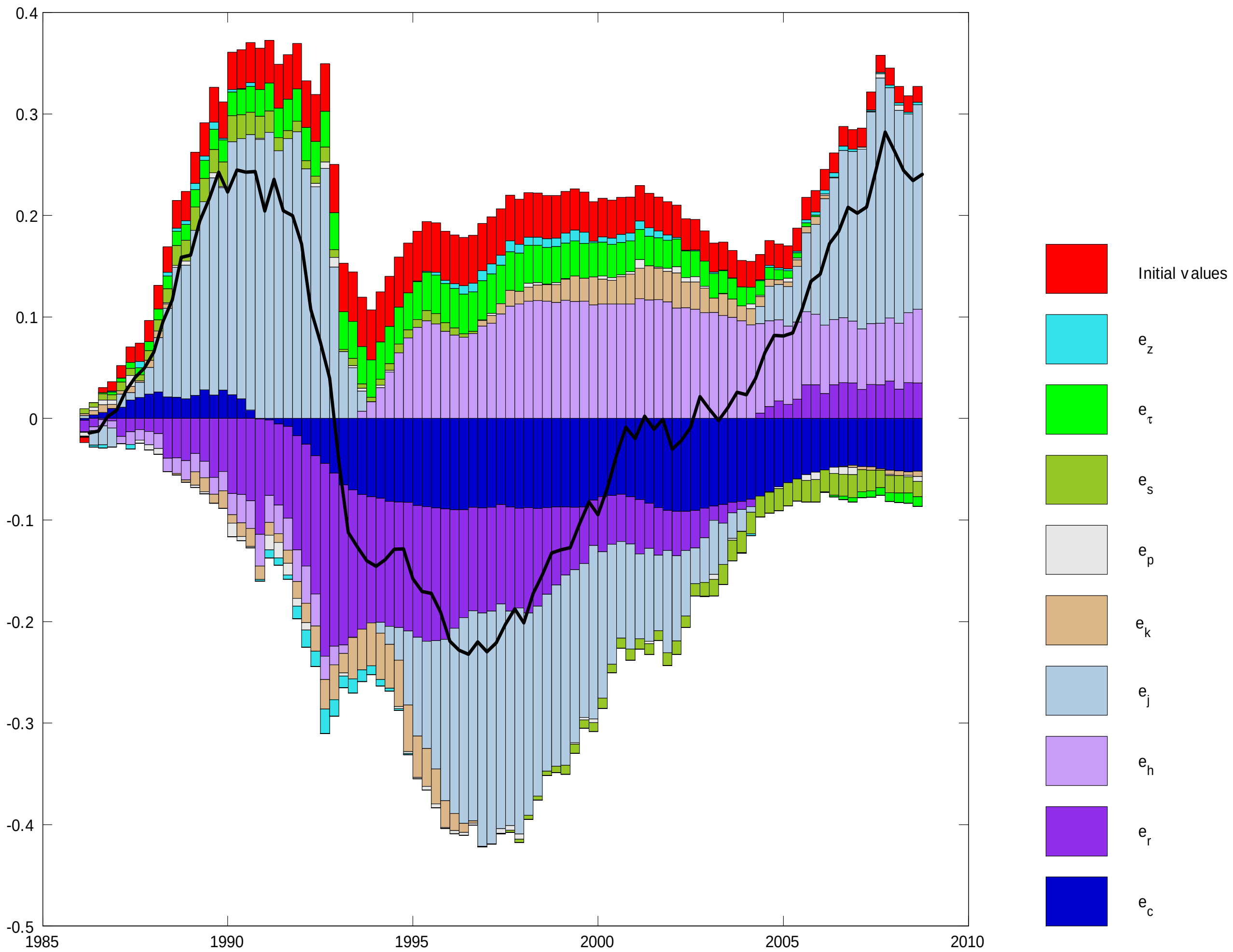

Figure 9. Historical shock decomposition for (detrended) real house prices q.

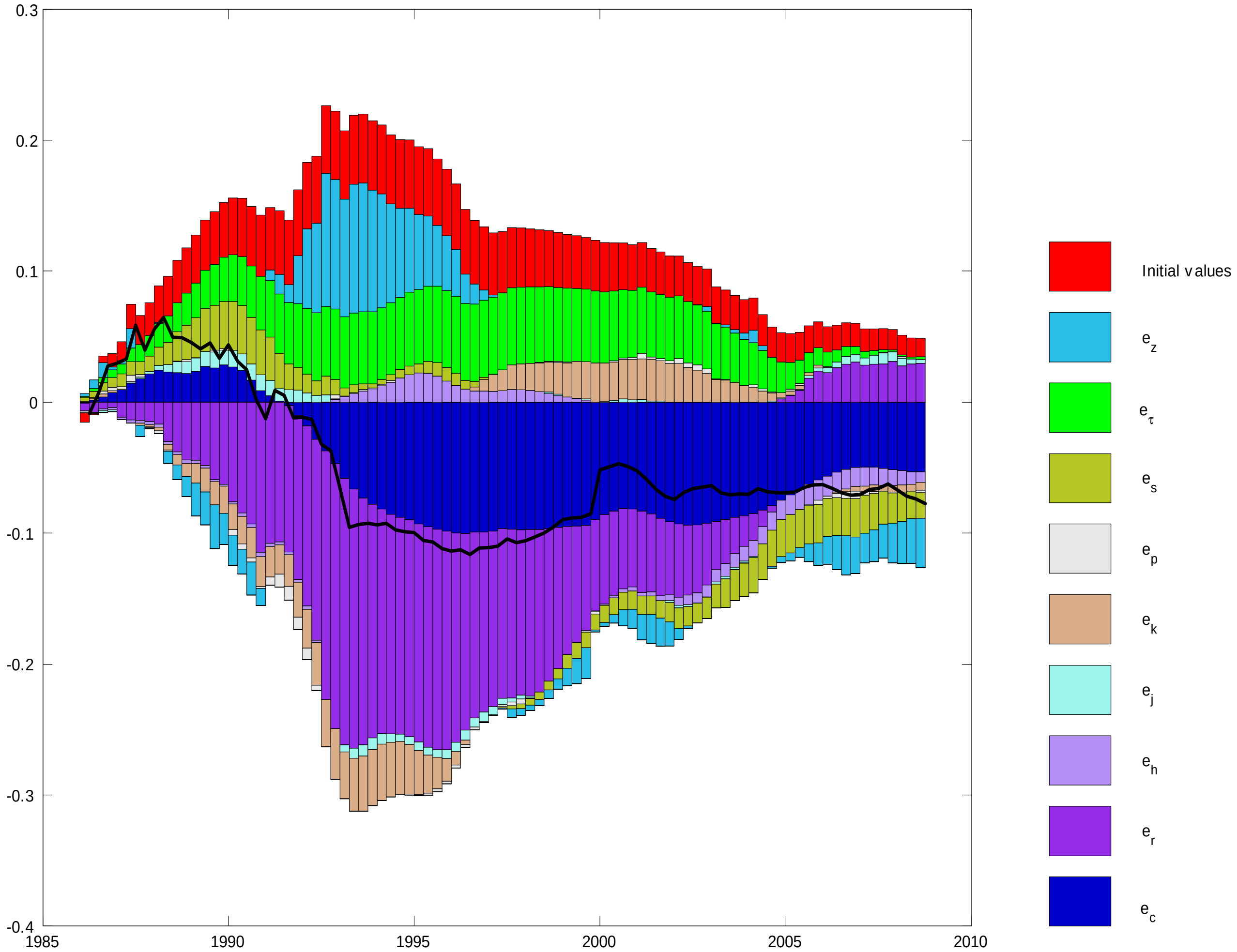

Figure 10. Historical shock decomposition for (detrended) aggregate consumption C.

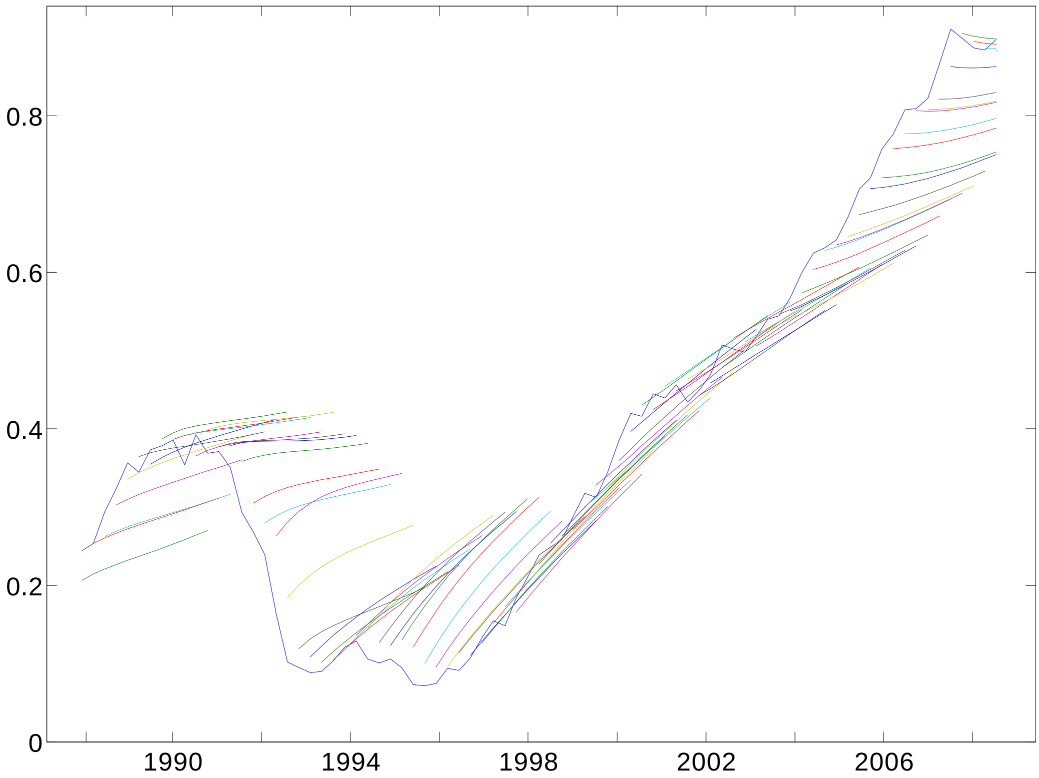

Figure 11. In-sample forecasts of real house price, q, 1988q3-2008q3.

A.2 Definition of investment adjustment cost function

The functions defining the investment adjustment costs are standard and can be written:

$$F\left(i_t, i_{t-1}\right) = \left(1 - \tilde{S}\left(\frac{G_C \Gamma_{AK} i_t}{i_{t-1}}\right)\right) i_t$$

$$\tilde{S}\left(x\right) = \frac{1}{2}\left\{\exp\left[\sqrt{\tilde{S}''}\left(x - G_C \Gamma_{AK}\right)\right] + \exp\left[-\sqrt{\tilde{S}''}\left(x - G_C \Gamma_{AK}\right)\right] - 2\right\}$$

This implies zero investment adjustment costs in steady state

A.3 Definitions of various parameters

$$\begin{aligned}
\Gamma_c &= \frac{G_c - \varepsilon}{G_c - \beta\varepsilon G_c} \\
\Gamma_c' &= \frac{G_c - \varepsilon'}{G_c - \beta'\varepsilon' G_c}
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{wc} &= \left(1 - \theta_{wc}\right)\left(1 - \beta G_c \theta_{wc}\right)/\theta_{wc} \\
\varepsilon_{wc}' &= \left(1 - \theta_{wc}\right)\left(1 - \beta' G_c \theta_{wc}\right)/\theta_{wc} \\
\varepsilon_{wh} &= \left(1 - \theta_{wh}\right)\left(1 - \beta G_c \theta_{wh}\right)/\theta_{wh} \\
\varepsilon_{wh}' &= \left(1 - \theta_{wh}\right)\left(1 - \beta' G_c \theta_{wh}\right)/\theta_{wh}
\end{aligned}$$

A.4 Data appendix

Aggregate consumption *(C)*: Real household consumption expenditure (incl. non-profit organisations, seasonally adjusted, base year 2000, Million SEK), divided by the population of working age (16 - 64). Source: Statistics Sweden.

Business fixed investment *(IK)*: Real Private Non-Residential Fixed Investment (seasonally adjusted, base year 2000, Million SEK), divided by the population of working age (16 - 64). Source: Statistics Sweden.

Residential investment *(IH)*: Real residential fixed investment (seasonally adjusted, base year 2000, Million SEK), divided by the population of working age (16 - 64). Source: Statistics Sweden.

Inflation *(π_4)*: 4-quarter log differences in the CPIX, which is an index used to compute underlying inflation. Before August 1998 we use the measure of underlying inflation called UND1, computed by Sveriges Riksbank. In August 1998 Statistics Sweden started publishing an index called UND1X, which is quite similar to UND1, on behalf of Sveriges Riksbank. In 2007 the name was changed to CPIX. Source: Statistics Sweden and Sveriges Riksbank.

Nominal short-term interest rate *(R)*: Nominal 3-month treasury bill rate (secondary market rate), expressed in quarterly units. Source: Sveriges Riksbank.

Real house prices *(q)*: Real estate price index for owner-occupied one- and two-dwelling buildings deflated with the CPIX. Source: Statistics Sweden.

Hours worked in consumption-good sector *(N_c)*: Total hours worked in the private sector less total hours worked in the construction sector (seasonally adjusted), divided by the population of working age (16 - 64). Source: Statistics Sweden.

Hours worked in housing sector *(N_h)*: Total hours worked in the construction sector (seasonally adjusted), divided by the population of working age (16 - 64). Source: Statistics Sweden.

Wage inflation in consumption-good sector *(w_{c4})*: 4-quarter log differences in the hourly wage. The wage is computed as gross pay (based on income statements) in the private sector divided by total hours worked in the private sector.

Wage inflation in the housing sector *(w_{h4})*: 4-quarter log differences in the hourly wage. The wage is computed as gross pay (based on income statements) in the construction sector divided by total hours worked in the construction sector.

The time series for real household consumption expenditure, total hours worked in the construction sector, business and residential investment was seasonally adjusted by us, using the US Census Bureau's X12-ARIMA program version 0.2.10 (log multiplicative). Wages and hours worked in the housing sector are not available and have been approximated by using data for the whole construction sector. The time series "Gross pay in the construction sector" (in Statistics Sweden, SM Am 61) has been linked by us to older series (in Statistics

Sweden, SM Am 28 for the period 1985q1-1985q3 and in SM Am 41 for the period 1985q4-1987q4). The gross pay reported in SM Am 41 for 1995q2 is clearly erroneous (Statistics Sweden has confirmed this). We have instead used the preliminary data for 1995q2, with an upward adjustment of 1 percent (the final data is usually adjusted upwards by 0 - 2 percent).

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