Housing collateral and the monetary transmission mechanism*

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March 2013

Abstract

This paper quantifies the effects of the recent increase in the housing loan-to-value (LTV) ratio on the monetary transmission mechanism. We set up a two sector DSGE model with collateral constraints and production of goods and housing. Using Bayesian methods, we quantify the component of the monetary transmission mechanism that is generated by housing collateral. We find that this component is substantial and strongly increasing in the LTV. We conclude that in order to properly understand the monetary transmission mechanism, we need to take into account the effects of housing related collateral constraints and their changing nature.

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

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

*The author thanks Matteo Iacoviello for his invaluable help with getting started on this paper and Peter Sellin and Magnus Jonsson for major contributions. I am also grateful for useful comments from Malin Adolfson, Mikael Carlsson, Matthieu Darracq Pariès, Daria Finocchiaro, Paolo Giordani, Jesper Hansson, Peter McAdam, Stefano Neri, Mattias Villani and seminar participants at Sveriges Riksbank, the ECB Workshop on the Housing Market and the Macroeconomy, the 2010 National Conference of Swedish Economists and ESEM 2011 (Oslo). The views expressed in this paper are solely the responsibility of the author and should not be interpreted as reflecting the views of the Executive Board of Sveriges Riksbank.

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1 Introduction

The role of housing in the macroeconomy has been discussed extensively in both policy and academic circles in recent years. The aim of this paper is to achieve a quantitative understanding of the role that housing and, in particular, housing collateral plays in the monetary transmission mechanism. We also document the effects of shocks to housing supply and housing demand on the broader macro economy. Our main exercise is to explore the implications of the increase in loan-to-value (LTV) ratios observed during the last two decades. These implications are particularly interesting due to recent policy discussions regarding regulations that set a legal maximum LTV. Such proposals are currently being entertained both at the national level in several countries and at the European Union level. In Sweden, a regulation was put in place on October 1st, 2010 that limits the LTV to a maximum of 85% (Swedish Financial Supervisory Authority, 2010).

Two previous papers provide he foundation of the relevant literature: Mishkin (2007) and Boivin, Kiley and Mishkin (2010). The former describes the various ways in which housing influences the monetary transmission mechanism. The latter is a broader analysis of how the monetary transmission mechanism has changed over time.

With the above 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. Loan contracts are in nominal terms. Wages and goods prices are sticky. Trends in house prices, residential investment and other real quantities are determined by sector-specific productivity trends. The model closely follows Iacoviello and Neri (2010), henceforth IN.[1] We choose to build on this model as it combines the collateral constraint mechanism with an explicit modelling of residential investment. It is therefore well suited to capture the business cycle implications of housing. Our only substantial improvement in terms of modelling is that we assume investment adjustment costs instead of capital adjustment costs. We show that this assumption generates more realistic gradual responses to shocks, particularly to monetary policy shocks. Together with sufficiently inelastic housing supply, investment adjustment costs also yield a comovement of business investment and residential investment in response to housing demand shocks.

To be able to perform quantitatively relevant exercises, we estimate our model using Bayesian methods on Swedish data from 1986Q1 to 2008Q3. From an international perspective, several aspects of the Swedish housing market are unusually well aligned with the assumptions made in a broad class of macro-housing models. Sweden is thus a suitable country on which to apply this type of model.

[1] Two key contributions to the literature on monetary DSGE models with housing collateral are Iacoviello (2005) and Aoki, Proudman and Vlieghe (2004), which use collateral constraints and costly external finance respectively.
A non-exhaustive list of other papers that explore housing collateral constraints in macro models are: Calza, Monacelli and Stracca (2011), Darracq Pariès and Notarpietro (2008), Finocchiaro and Queijo von Heideken (2009), Liu, Wang and Zha (2009) and Piazzesi and Schneider (2008).

We will now go through the main results, their intuition and their implications. Our main qualitative results are that: i) Housing used as collateral for loans reinforces the effects of monetary policy shocks and housing demand shocks, and ii) a higher maximum LTV implies additional amplification. The intuition for these results is as follows. The demand for consumption goods and housing by constrained households increases in their net worth. Shocks that move house prices and the variable in question, e.g. GDP, in the same (opposite) direction imply that collateral constraints amplify (reduce) the response of that variable. Both monetary policy shocks and housing demand shocks move all variables of interest in the same direction as house prices, and collateral constraints accordingly amplify these shocks.

Regarding the fact that the degree of this amplification is increasing in the LTV, note that household leverage is increasing in the LTV. This implies that, for a given change in house prices, the change in net worth of constrained households is larger and the demand effect from collateral constraints is accordingly increasing in the LTV.

Our assumption of nominal loan contracts is key for the result that only some shocks generate large collateral effects. In the presence of nominal loan contracts, an unexpected increase in inflation reduces the real value of nominal debt, an effect known as Fisher debt-deflation. Only shocks that move house prices and inflation in the same direction result in both effects (house price capital gains and the Fisher debt-deflation) affecting the net worth of constrained households with the same sign, and only then do we obtain large collateral effects.

The main quantitative results of the estimated model are:

i) Households accounting for one fifth of the labor income share, are estimated to be collateral constrained. This implies that household balance sheets substantially affect key macro variables. Specifically, collateral constraints cause 8% of the monetary policy shock effect on inflation, 9% on GDP and 26% on consumption.

ii) As mentioned above, the collateral component of the monetary transmission mechanism is increasing in the maximum LTV ratio. When the LTV is increased from 85% to 95%, the size of the collateral effect on the response of inflation increases by roughly 40%. For GDP and consumption the collateral effect increases by roughly 90%. The reverse happens when LTV is reduced. Thus, the recent Swedish regulation that caps LTV at 85% will reduce the collateral effect substantially, thereby reducing the strength of the monetary transmission mechanism.

iii) An increased LTV also makes housing demand shocks more powerful. Changing LTV from 85% to 95% more than doubles the effect of housing demand shocks on most macroeconomic variables.

iv) We confirm that only shocks that move house prices and inflation in the same direction generate large collateral effects. This implies that for most shocks, excluding monetary policy shocks and housing demand shocks, the quantitative importance of collateral constraints is limited.

v) Nevertheless, because of the amplification of shocks detailed above, the volatility implied by the model increases if the LTV is increased from 85% to 95%. In particular, the standard deviation of GDP increases, by 5%, driven entirely by a 12% increase in the standard deviation of consumption. In terms of policy prescription, a reduction in the LTV, such as the recent Swedish LTV cap, reduces volatility of GDP and aggregate consumption. In this respect, the LTV cap is therefore a beneficial policy.

vi) Demand and supply shocks to housing only explain a very small fraction, less than 2%, of the fluctuations in GDP and inflation.

We draw two main conclusions from these results. First, 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 LTV ratios or, more broadly, household indebtedness has increased substantially in the last decade implies substantial amplification of certain shocks on both housing and the macroeconomy more generally.

Second, 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. This is consistent with the results in Bjørnland and Jacobsen (2010) using different methods. We caution that both our DSGE model and the VAR in Bjørnland and Jacobsen (2010) have a linear (linearized) structure and thus do not fully capture non-linearities caused by occasionally binding credit constraints, for example.

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

1.1 The Swedish housing sector – in line with model assumptions

One reason for using Swedish data to estimate macro-housing models is that Swedish housing characteristics are more in line with the assumptions made in this family of models than in most other countries. First, the models assume that mortgages have variable interest rates. For Sweden, this assumption is reasonable as the country has a high fraction of mortgages with variable interest rates. The share of mortgages with variable interest rate since 1996 has averaged roughly 50%, and in recent years has been as high as 90%.[2] Furthermore, the mortgages with fixed rates tend to be fixed for short horizons such that there is only a negligible fraction of loans with interest rates fixed for longer than 5 years. Assenmacher-Wesche and Gerlach (2009) show that the response of GDP and house prices to monetary policy shocks is substantially faster in countries with a high fraction of variable interest rate loans. Calza *et al.* (2011) find stronger responses to monetary policy shocks for

[2] Reliable data on this fraction prior to 1996 is not available.

consumption, residential investment and house prices for countries with both "high financial development" and predominantly variable interest rates.

Second, because of heavy regulation such as rent control, the rental housing market is very rigid, at least in the three major metropolitan areas. Thus, the assumption of no substitution between owner-occupied housing and rentals is approximately satisfied.

Finally, Swedish personal bankruptcy law is relatively strict with virtually no way to walk away from personal debt. This removes a non-linear decision problem from the economy, and makes it easier to model using standard linear methods.

2 Model

2.1 Overview

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

The financial constraint in the model applies to households, who 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. 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.

We model a closed economy. This choice is motivated by simplicity and the fact that housing demand and housing supply are local, and thereby domestic activities.

2.2 Households

We let primes denote the variables and parameters that are specifically related to impatient households. For patient households, the expected lifetime utility is given by:

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

and for impatient households by:

$$E_0 \sum_{t=0}^{\infty} \left(\beta' G_c\right)^t z_t \left(\begin{array}{c} \Gamma'_c \log\left(c'_t - \varepsilon' G_c c'_{t-1}\right) + j_t \log h'_t - \\ \frac{\tau_t}{1+\eta'} \left(\left(n'_{ct}\right)^{1+\xi'} + \left(n'_{ht}\right)^{1+\xi'} \right)^{\frac{1+\eta'}{1+\xi'}} \end{array} \right) \tag{2}$$

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 is a shock in the demand for housing and τ_t is 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). More loosely, ξ is a measure of the labor immobility between sectors. Finally, G_C is the gross growth rate of consumption in the steady state and Γ_c and Γ'_c are scaling factors, defined in section A.4, that ensure 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. In other words, 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. The patient households choose the capital utilization rate and rent out capital services to firms. They maximize their utility, (1), subject to the budget constraint:[3]

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

where i_{ct} and i_{ht} denote investment in capital for each of the two production sectors, A_{kt} denotes the investment-specific technology in the goods sector, 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

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

that loan contracts are in nominal terms. The ex-post real return is therefore obtained by dividing the nominal risk-free interest rate, R_{t-1}, with the inflation rate, π_t. Letting bonds have nominal payoffs is empirically well founded and allows for the Fisher debt-deflation mechanism.

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

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

Second, the collateral constraint:

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

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 will prefer to borrow the maximum amount in order to consume more today rather than in the future.

2.3 Firms and technology

There are two types of firms. First, there are competitive producers of the homogenous good that use capital and labor to produce the non-housing good, Y_t, as well as capital, labor, land and the intermediate input to produce new houses, IH_t. They maximize the following profit function:

$$\frac{Y_t}{X_t} + q_t IH_t - \left(\sum_{i=c,h} w_{it} n_{it} + \sum_{i=c,h} w'_{it} n'_{it} + R_{ct} z_{ct} k_{ct-1} + R_{ht} z_{ht} k_{ht-1} + R_{lt} + p_{ot} o_t \right)$$

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

$$\begin{aligned} Y_t &= \left(A_{ct} \left(n_{ct}^{\alpha} \left(n'_{ct} \right)^{1-\alpha} \right) \right)^{1-\mu_c} \left(z_{ct} k_{ct-1} \right)^{\mu_c} \\ IH_t &= \left(A_{ht} \left(n_{ht}^{\alpha} \left(n'_{ht} \right)^{1-\alpha} \right) \right)^{1-\mu_h-\mu_o-\mu_l} \left(z_{ht} k_{ht-1} \right)^{\mu_h} o_t^{\mu_o} l_{t-1}^{\mu_l} \end{aligned}$$

where A_{ct} is the productivity in the goods sector and A_{ht} is 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 use the time subscript associated with the period during which a quantity is determined.

We assume investment adjustment costs of the type introduced in Christiano, Eichenbaum and Evans (2005). The law of motion for capital in the two respective production sectors are:

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

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

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

The second type of firm is a monopolistically competitive retailer 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 are allowed to chose 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.[4] We allow for an i.i.d. cost-push shock to enter directly into 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.[5] The resulting four wage equations, one for each sector-household pair, are documented 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 these assumptions generate positive comovement of production in the two sectors, coinciding with what we observe empirically.[6]

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):

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

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

[5] Households supply labor to labor unions that differentiate it and set sticky wages. Labor packers then assemble this differentiated labor into to the homogenous composites n_c, n_h, n_c' and n_h'.

[6] This is generally acknowledged in the durable goods literature, and was recently emphasized as a sufficient condition in standard settings without collateral constraints by Sterk (2009).

where GDP is the sum of the value added of the two sectors at steady state house prices, $GDP_t = Y_t + \bar{q}IH_t - o_t$.[7] ρ_R is the degree of interest rate smoothing, r_π measures the interest rate response to inflation. $r_{\Delta y}$ denotes the interest rate response to deviations of GDP from its steady state growth rate G_C. $e_{r,t}$ 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. As noted by Christiano, Trabandt and Walentin (2011), the timing of the Taylor rule is unusually important because of the presence of the debt-deflation mechanism. This mechanism tends to become too strong if the central bank reacts to lagged inflation.

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:

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

Finally, we assume a 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 the letter e, with a subscript specifying the type. The standard deviations of these innovations are 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.

[7] We choose steady state house prices as using current house prices here would be unfortunate because it would imply a "built-in" interest rate response to house prices.

2.6.1 Technology shocks and trends

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

$$\begin{aligned}
\log A_{ct} &= t\log(1+\gamma_{AC}) + \log a_{ct} \\
\log A_{ht} &= t\log(1+\gamma_{AH}) + \log a_{ht} \\
\log A_{kt} &= t\log(1+\gamma_{AK}) + \log a_{kt}
\end{aligned}$$

such that a_{ct} 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 remaining productivity processes. The stochastic part of the productivity processes follow:

$$\begin{aligned}
\log a_{ct} &= \rho_{AC}\log a_{ct-1} + e_{ct} \\
\log a_{ht} &= \rho_{AH}\log a_{ht-1} + e_{ht} \\
\log a_{kt} &= \rho_{AK}\log a_{kt-1} + e_{kt}
\end{aligned}$$

The model implies the following relationships between the above productivity trends and the implied trends for the real variables.

$$G_c = G_{IK_h} = G_{IH}G_q = 1 + \gamma_{AC} + \frac{\mu_c}{1-\mu_c}\gamma_{AK} \tag{9}$$

$$G_{IK_c} = 1 + \gamma_{AC} + \frac{1}{1-\mu_c}\gamma_{AK} \tag{10}$$

$$G_{IH} = 1 + (\mu_h + \mu_o)\gamma_{AC} + \frac{\mu_c(\mu_h+\mu_o)}{1-\mu_c}\gamma_{AK} + (1-\mu_h-\mu_l-\mu_o)\gamma_{AH} \tag{11}$$

$$G_q = 1 + (1-\mu_h-\mu_o)\gamma_{AC} + \frac{\mu_c(1-\mu_h-\mu_o)}{1-\mu_c}\gamma_{AK} - (1-\mu_h-\mu_l-\mu_o)\gamma_{AH} \tag{12}$$

Here G_c denotes the deterministic trend in consumption. G_{IKc} and G_{IK_h} denote the trend of investment in goods producing capital and house producing capital, respectively. G_{IH} denotes the trend growth of house production, and thereby the housing stock, and G_q is the trend in real house prices.

From the first equation, we see that consumption, house producing capital and housing expenditure ($G_{IH}G_q$) grow at a rate jointly determined by goods productivity growth, γ_{AC}, and investment-specific productivity growth, γ_{AK}. The same terms affect the trend in residential investment G_{IH}, but are 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_{IH} and G_q is identical except that it has opposite signs: house production is increasing in γ_{AH} while house prices are decreasing in γ_{AH} by the same amount.

3 Estimation

3.1 Data

Our data sample covers Sweden from 1986Q1 to 2008Q3. We choose to start our sample period in 1986Q1 as this is the first quarter in which the official real estate price index is available, and ensures that the sample covers more than one house price cycle. Further, 1986Q1 roughly coincides with the end of the period of bank and financial regulatory liberalization. A potential problem with our sample period is that the monetary policy regime changed: the fixed exchange rate regime collapsed in the 4th quarter of 1992 but the *de jure* inflation targeting regime was not instated until the 1st quarter of 1995.

We use 10 data series for the estimation: Aggregate consumption (C), business fixed investment (IK), residential investment (IH), four-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), four-quarter wage inflation in consumption-good sector (w_{c4}), four-quarter wage inflation in the housing sector (w_{h4}). We have chosen four-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.[8] The data series used in the estimation are plotted in Figure 1 and documented in detail in the Data Appendix.

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 the values coincide to a very large degree with the calibration in IN. A key parameter worth mentioning is the LTV ratio, m, which we set to 85%. In Sweden over our sample period 1986-2008, the LTV likely increased, but with little high quality data available to confirm this trend, particularly not on a quarterly frequency, we restrict the parameter to be constant. Our model only includes the private sector and the value of residential investment as fraction of private sector GDP in our sample period is 6.3%. We therefore set $j = 0.11$ to obtain $q * IH/GDP$ roughly equal to 6.3% at the prior mode.

We set the steady state annual inflation target to 2%, matching the official stated target of Sveriges Riksbank.[9] β is set to yield a 2.25% annual real interest rate. The discount factor for the impatient households, β', is set substantially below β in order to ensure that the collateral constraint is always binding.

Based on results from initial estimations, we calibrate all three indexation parameters

[8] See Lindé (2003) for documentation of the problems with first difference inflation measurement in Swedish data, and how fourth difference inflation reduces the problem.

[9] 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.

to zero so that they reflect absence of indexation.[10]

3.3 Priors

The priors are documented in Tables A2 and A3. The trend parameters and the shock standard deviations are scaled in order to obtain a prior standard deviation of the same order of magnitude as that of other parameters. This is done for computational reasons in order to facilitate the optimization. For several parameters we use identical priors to IN. While we use a less informative prior than IN, we follow IN by centering the prior for α at 0.65.

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

Apel, Friberg and Hallsten (2005) show, using microlevel survey data, that goods prices change roughly every year in Sweden. Accordingly, we center our prior for θ_π at 0.75. We set our prior for wage setting in the goods industry similarly. For the housing sector, 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 limited labor movement between the two sectors by using less informative priors with high means for ξ and ξ', the curvature of the disutility of working in a given sector.

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

We center all shock persistence parameters 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 data series: w_{c4}, w_{h4} and IH. Both wage series are measured with substantial error, e.g. indicated by a recent data revision by Statistics Sweden that affected data going more than 10 years back. We also allow for measurement errors in residential construction hours because we only have a data proxy (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

[10] In exploratory estimations the posterior means of both ι_{wc} and ι_π were close to zero, and data appeared to contain no information about ι_{wh}.

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 posteriors

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 (9-12): 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 2 for a plot of these data series 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 one fifth. The sectorial labor mobility is estimated to be very low, corresponding to high values of ξ and ξ' around 5. In 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 indicates 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 1, where the smoothed variables (not incorporating measurement errors) are plotted against the data.[11]

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.

4.1.1 Comparison to the literature

Comparing our estimation results to those in IN we note that labor mobility between the housing and the consumption-good sector, unsurprisingly, is substantially lower in Sweden than in the US. Additionally, we find that housing sector wages are more flexible than non-housing sector wages. Our estimate of the Taylor rule parameter, $r_{\Delta y} = 0.15$, is between IN's higher estimate and the lower values found in most of the literature (Smets

[11] We have confirmed that the posterior parameter distributions are only 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.

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_{IH}. We therefore arrive at a negative estimate of G_{IH} and, accordingly, (see equations (9)-(12)) find that house prices grow faster than consumption, $G_q > G_c$. Other methods also indicate negative change in the productivity of the housing sector during our sample period, see Boverket (2002), similarly to Corrado *et al.* (2007)'s results 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 productivity trend – is the decrease in government subsidies and increase in taxes (VAT on building materials) on residential investment that occurred in the beginning of our sample period, in 1991. 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 construction: land. However, no such trend is evident in the available data.[12]

4.2 Impulse response functions

The impulse response functions (IRF) for a monetary policy shock at the posterior mean is displayed in Figure 3. In this subsection, we analyze the estimated benchmark results which are shown in the figures using a solid line. An 80 annualized basis points (ABP) temporary increase in the interest rate yields 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 initially jumps down and decreases by a factor of four 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.

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

The IRF for a housing preference (housing demand) shock, e_j, is displayed in Figure 4. Note that this shock is highly persistent with an AR(1) coefficient of 0.97 such that, in

[12] The land price and construction cost data is from Statistics Sweden, SCB (2010), p. 134 and SCB online. It indicates that i) land costs as a fraction of the cost of new houses is not increasing over the sample period, and ii) the 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. But, one should interpret this data carefully as there is a potential sample selection problem because land with new residential construction plausibly are in less attractive areas than the existing housing stock, see Davis and Heathcote (2007).

contrast to the monetary policy shock, most 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. In contrast to IN, we obtain a positive business investment response at the impact of the shock. This business investment is made to satisfy the future high demand for both housing and non-durable consumption. The investment adjustment costs deter postponing this investment. In addition to non-negligible investment adjustment costs, low sectorial labor mobility is needed to generate this response. The latter implies a steeper housing supply curve. This limits the amount of resources that is channeled into residential investment and instead generates an increase in non-durable goods consumption because of the increase in house prices that yield a relaxation of collateral constraints.

In Figure 5, we illustrate the IRF of a shock to the consumption good technology, e_c. This IRF is conventional and implies an initial decrease in inflation and the interest rate, as well as an increase in business investment and aggregate consumption. Interestingly, residential investment initially decreases despite that house prices increases on impact.

4.2.1 The importance of collateral constraints – IRFs

To quantify the effects of collateral constraints, we now compare the impulse responses across model specifications, keeping the estimated parameters fixed at their posterior mean values. The results for the monetary policy shock are summarized in Table 1 and the dynamics are plotted separately in the same figure as the benchmark monetary policy IRF in Figure 3. 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 amplitude (i.e. the peak response) of the impulse responses, we note that the collateral effect accounts for a non-negligible part of the responses in terms of amplitude: 8% for inflation, 9% for GDP and 26% for aggregate consumption. The first row of Table 1 summarizes these results.

	π	GDP	C
Fraction of amplitude from collateral constraint	8.3	9.2	26.0
Increase in amplitude as LTV increased from 85% to 95%	3.5	8.3	24.0

Table 1: Collateral constraint component as a fraction of total monetary transmission. Measured in terms of amplitude of impulse response function.

The second row of Table 1 and the dashed line in Figure 3 illustrate the dynamics if the maximum LTV, m, is set to 95% instead of our benchmark 85%, similarly to what happened in the most recent decade in Sweden and most other OECD countries.[13] With

[13] We keep the fraction of collateral constrained households fixed, which might be a debatable assumption, but no clear alternative exist.

higher LTV, the impatient households are more heavily indebted and leveraged. Demand of constrained households for consumption goods and housing is increasing in their net worth. This higher leverage implies that for a given change in house prices the change in net worth of constrained households is larger and the demand effect from collateral constraints is accordingly increasing in the LTV. Quantitatively, we find that, in response to a contractionary monetary policy shock, constrained households 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 leads to smaller effects of monetary policy on residential investment.[14] General equilibrium effects make business investment and the consumption of patient households decrease more as well, but the additional effect on inflation is small at 3.5%. The amplitude of the impulse response of GDP is 8% larger and for aggregate consumption 24% larger. Comparing the two rows in Table 1, we note that when LTV is increased from 85% to 95%, the size of the collateral effect on the response of π increases by roughly 40% and of GDP and consumption by roughly 90%. Calza *et al.* (2011) show qualitatively that an increased LTV implies more shock amplification and we are here able to quantify it in an estimated model. Our results also relate to Iacoviello and Minetti (2003). They set up a small open economy model where international borrowing is constrained as a fraction of the value of the housing stock. Relaxation of that constraint is shown to amplify the effect of monetary policy shocks on house prices.

It is important to point out that financial development that increases households' access to finance in terms of higher LTV amplifies the effects of some demand shocks – such as monetary policy shocks and housing demand shocks (see below).

To put this in context, note that our results also imply that most of the effects of monetary policy are unrelated to housing related collateral constraints. Even for an LTV of 95%, Table 1 can be read as roughly 80% of the effect on GDP, and almost 90% of the effect on π, coming from other channels, notably those that affect business investment. What we have emphasized here is merely that the part of the transmission mechanism that is related to collateral constraints is highly sensitive to the LTV.

Switching to the housing preference shock plotted in Figure 4 and comparing the benchmark model to the specification without collateral constraints, we note the importance of the collateral effect for this shock. That is, all the expansionary effect of the housing demand shock on inflation and consumption comes from the collateral effect.

Comparing the IRF for an LTV of 95% to the benchmark also shows large differences: The impact of the shock more than doubles for aggregate macro variables (i.e. not including

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

[14] 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.

IH and q). This points to the increased importance of housing shocks in recent years, and more generally, to the importance of fully understanding what, in the absence of binding regulation, 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. Shocks that push house prices and goods inflation in opposite directions, e.g. consumption good technology shocks, imply two counteracting effects on borrowers' net worth, such that the collateral effect tend to be roughly zero. Furthermore, the direction of the collateral effect is dampening for shocks that push the variable in question in the opposite direction as house prices and/or inflation - e.g. a housing technology shock which increases residential investment while decreasing house prices.

To understand the importance of price and wage rigidities for the effect of LTV on macro implications we perform the same comparison of collateral effects for 85% and 95% LTV, but for flexible prices and wages. We find that these rigidities do not matter for the result. Also in that specification, amplitudes of all real quantities are larger for a higher LTV in the case of housing preference shocks, and virtually invariant in the case of consumption good technology shocks. IRFs for these specifications are documented in the Computational Appendix.

4.3 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, from a shock perspective, the large degree of macro-housing disconnect: the housing technology shock, e_h, accounts for three quarters of the variance in residential investment and the housing demand shock, e_j, accounts for three quarters of the variance in house prices. At the same time, the housing technology shock and the housing demand shock contribute less than 1% of the variance of GDP and aggregate consumption, and 0% 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 are 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 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. Residential investment is instead mainly affected by the monetary policy shock, e_r, and the labor supply shock, e_τ.

The two housing shocks are substantially more important for GDP and consumption at the one quarter horizon than at the eight quarter horizon. Also the monetary policy shock is more prominent at the one quarter horizon, both for house prices and macro variables, while technology shocks matter less. Finally, we note that the importance of a shock for a variable tend to vary monotonically with the forecast horizon, and we therefore refrain from commenting on the results for the 20 quarters horizon.

4.3.1 The importance of collateral constraints – variance decomposition

To complement the analysis in section 4.2.1 and further illustrate the importance of the LTV for the transmission mechanism, we redo the variance decomposition setting the LTV to 95%, keeping all other parameters fixed. We compare these variance decomposition results to the benchmark 85% LTV case. In particular, in Table 2, we report the percentage change of the fraction of the variance accounted for by the monetary policy shock for three different forecast horizons. The changes are large for the one quarter horizon, and decreasing in the horizon. This exercise confirms the basic message from section 4.2.1 that increasing the maximum LTV substantially amplifies the monetary transmission mechanism, and that this amplification is strongest in C followed by GDP and then π.[15] For shorter horizons, the variance decomposition results also turn out to be quantitatively similar to what we obtained for the IRF amplitudes.

Performing the same exercise for the housing preference shock, e_j, we find that the increase in the importance of this shock is very large and decreasing in the horizon: 200% to 500% for GDP and 600% to 1200% for consumption, but from a very low level for both variables. The importance of the housing demand shock for π is negligible, regardless of the LTV.

Note that increasing the LTV to 95% also has implications for the total variance implied by the model. Volatility of inflation, business investment and housing sector variables are unaffected, but the standard deviation of GDP increases by 5%. This is entirely driven by an increase of the standard deviation of C by 12%. The increased volatility that we find contrasts with the results of Campbell and Hercowitz (2006). In their theoretical model, GDP volatility decreases in the LTV, mainly because their key mechanism is an effect from housing demand (demand for internal funds) on labor supply and their choice to restrict attention to TFP shocks. With that mechanism, higher LTV generates less procyclical labor supply. Importantly, their setup differs from ours in that patient households ("savers", in their terminology) do not supply labor.

[15] Clearly, at some level, the same information is contained in the IRFs as in the variance decomposition, but we find it informative to also report the result in this form (i.e. for fixed horizons instead of for the peak response).

Horizon	π	GDP	C
1	6.6	19	27
8	5.3	9.0	14
20	4.7	6.7	10

Table 2: Effect of changing LTV from 85% to 95% on the importance of the monetary policy shock for variance decomposition. Measured as percentage change of the fraction of the variance accounted for by the monetary policy shock.

4.4 Historical shocks and shock decomposition

The smoothed values of the shock processes are displayed in Figure 6. In line with the variance decomposition, it seems that construction sector productivity, a_h, follows the data series for residential investment while the housing preference shock process, j, more closely follows the house price series. Part of the decrease in housing sector productivity in the early 1990's might consist of the increased taxes mentioned in section 4.1.[16] 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 at that time. The housing preference shock tends to soak up any change in housing demand, including those caused by changed taxation on house owners, such as limitations on interest rate deductions around 1991 and the decreased residential property tax announced in 2006-2007.

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 several large contractionary monetary policy shocks.

In Figure 7, 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, for the period 1990-2004 points to the very long-lived effects of monetary policy in this model on housing variables. This characteristic is also evident from the monetary policy impulse response function discussed above. Since 2005, monetary policy shocks have somewhat contributed to the high level of q. We note that the housing demand shock, e_j, had positive contribution to q around 1990, a negative contribution 1994-2003 and was an important reason for q being above trend 2004-2007. The negative housing technology shock, e_h, has had positive impact on q since 1994, but this has been partially offset by consumption technology shocks, e_c.

Shock decomposition for aggregate consumption is documented in Figure 8. The main point we want to illustrate here is that shocks to the housing sector have not been important for consumption which is consistent with the variance decomposition. In spite of

[16] The model allows for variable capital utilization, and the smoothed utilization series looks reasonable. Thus, we do not think that contamination of the housing TFP series from inappropriate assumptions on capital utilization has occurred.

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.

4.5 Validation and robustness

In this section, we provide three forms of validation of our model. First, we compare the business cycle moments of the model to the data. Second, we evaluate our model's forecast performance with a focus on house prices. Third, we compare the model's monetary policy impulse response to a structural VAR estimate. In addition, we perform a robustness exercise by changing the sample period used for estimation.

4.5.1 Business cycle moments

Table A5 contains the business cycle moments for the data and the model, both Hodrick-Prescott filtered. 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, IH, and GDP are less correlated.[17]

Our estimated model successfully matches the standard deviation of key variables, except that it overpredicts the volatility of aggregate consumption, C. The autocorrelations implied by the model are roughly in line with the data, with the most notable discrepancy being the underprediction of the autocorrelation of IH and q.

Regarding correlations, the model matches the data well except in one dimension: There are large underpredictions of the correlations between q and the real quantities GDP, C, and IH. 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 overstates their comovement.

4.5.2 Forecast performance

Another suitable dimension for evaluating the empirical performance of a DSGE model is its forecast performance. We focus our attention on the real house price, q. The general view in the literature is that house prices have a predictable component (Cho, 1996 and Corradin, Fillat and Vergara-Alert, 2010). For forecasting purposes, we re-estimate the

[17] It should be noted that residential investment lags GDP in Sweden. This is different from almost all other OECD countries where residential investment leads the business cycle. But, the Swedish pattern appears to be changing over time and residential investment did not lag output in the most recent recession. 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.

model on the first half of the sample, i.e. 1986Q1-1997Q1, and perform an out-of-sample forecast evaluation. We also generate in-sample forecasts using the model estimated on the full sample. The in-sample forecasts are plotted in Figure 9. The estimated positive trend in house prices generates increasing forecast paths, except for the last quarters of the sample. For the latter period, we instead obtained decreasing forecast paths for q as house prices had moved far above trend. The recent turning point/slowdown in house prices was predicted to happen long before it actually took place. In other words, the model incorrectly predicts the timing of the turning point, but accurately captures the underlying tendency.

In Table A6 we document the root mean square error (RMSE) for the real house price forecast, for one to twelve quarters forecast horizon both in-sample and out-of-sample. For comparison purposes we also report the RMSE of a deterministic linear trend estimated on the corresponding sample period (always starting at the current house price when used for forecasting). The in-sample DSGE model forecasts have a lower RMSE than the trend on horizons of eight quarters and longer, and similar RMSE on short horizons. For out-of-sample forecasts, the DSGE model dominates the linear trend on all horizons. On 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]

4.5.3 VAR evidence

Bjørnland and Jacobsen (2010) estimate a structural VAR for Sweden for a time period that roughly coincides with our sample. Their six variable VAR includes both macro variables and house prices. They find monetary policy shock IRFs that are remarkably similar to our DSGE results both in terms of magnitude and shape. The only notable difference from our model is that they obtain a more gradual response of inflation. They also find that, in terms of variance decomposition, the contribution of house price shocks to macro variables is very moderate, 4-10%, with GDP in the low end of this interval. This result is also in line with our estimated DSGE model.

4.5.4 Re-estimation on shorter sample

For robustness purposes, we re-estimate the model on a subsample, setting the start date to coincide with the official inflation target regime, 1995Q1. The parameter estimates are generally very similar to the benchmark, full sample estimates, and in particular this is true for the coefficients in the Taylor rule as well as for the fraction of constrained households, $1-\alpha$. The exceptions to this similarity are the estimated productivity trends and a group of parameters indicating more sluggish adjustment in the post-1995 sample: lower sectoral labor mobility (i.e. high ξ), higher capital adjustment costs, S''_c, higher cost of variable capital utilization, ζ, and stickier consumption good wages, θ_{wc}. These subsample

[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).

parameter estimates are documented in the Computational Appendix, together with plots of the subsample monetary policy impulse responses.

The reason that this subsample estimation is not our benchmark is that we strongly suspect that the estimated trends are adversely affected by the short sample. In particular, for 1995-2008, we only cover half of a housing cycle, just one through-to-peak move (see Figure 2). The data series measured in levels (C, IH, NH and q) end up far from the trends and this is consistent with (and plausibly causing) the high estimated degree of sluggishness.

With this caveat in mind, we redo our main exercise using the subsample estimates. The results regarding the importance of the collateral constraints and the effect of changing LTV are documented in Table 3. Comparing these results to our benchmark results in Table 1, we note that the presence of collateral constraints for the monetary transmission mechanism on inflation and consumption is roughly unchanged. For GDP, and more generally for an increase in the LTV, the effects are substantially smaller for this estimation than for our benchmark. The effect on the amplitude of the GDP impulse response from changing LTV is smaller mainly because the amplification of the collateral effects on consumption and residential investment are less synchronized.

	π	GDP	C
Fraction of amplitude from collateral constraint	7.5	3.5	19.1
Increase in amplitude as LTV increased from 85% to 95%	2.8	1.2	12.0

Table 3: Collateral constraint component as a fraction of total monetary transmission. Measured in terms of amplitude of impulse response function. Robustness version, model estimated on 1995q1-2008q3.

5 Summary and conclusions

We developed a monetary DSGE model with two sectors and a role for housing as collateral. To perform quantitatively relevant exercises, we estimated the model using Bayesian methods on Swedish data. We validated the performance of the model in terms of business cycle moments, forecast performance, and its similarity to the monetary policy shock impulse response obtained by using a structural VAR.

In our main exercise, we quantified the component of the monetary transmission mechanism that is generated by housing collateral. We found that this component is a non-negligible fraction of the impulse response and strongly increasing in the LTV. The collateral effects of housing demand shocks are also strongly increasing in the LTV. Our second main result is that shocks *originating* in the housing sector have quantitatively negligible effect on macroeconomic variables like inflation and GDP.

In other words, housing collateral is important for amplification of some shocks, especially in a setting with high LTV, but housing is not an important source of business cycles. Regarding the latter result, we are well aligned with Bjørnland and Jacobsen (2010), but contradict Leamer (2007), although his work does not impose the same level of structure and concerns a different country.

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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_π	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 %
$\sigma_c 100$	inv-Γ	4.0	2	1.716	0.141	1.483	1.939
$\sigma_r 1000$	inv-Γ	5.0	2	3.483	0.327	2.952	4.005
$\sigma_h 100$	inv-Γ	4.0	2	4.811	0.391	4.177	5.447
$\sigma_j 10$	inv-Γ	0.7	2	1.303	0.378	0.694	1.870
$\sigma_k 100$	inv-Γ	4.0	2	5.843	1.513	3.390	8.264
$\sigma_p 1000$	inv-Γ	5.0	2	5.504	0.500	4.674	6.290
$\sigma_s 1000$	inv-Γ	1.0	2	1.870	0.347	1.324	2.426
$\sigma_\tau 10$	inv-Γ	0.6	2	0.918	0.185	0.615	1.208
$\sigma_z 100$	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 (%)		Autocorrelation	
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
IH	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, IH	0.46	0.35		
GDP, q	0.82	0.21		
q, C	0.62	0.30		
q, IH	0.47	0.10		
IK, IH	0.01	0.18		
C, IH	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.

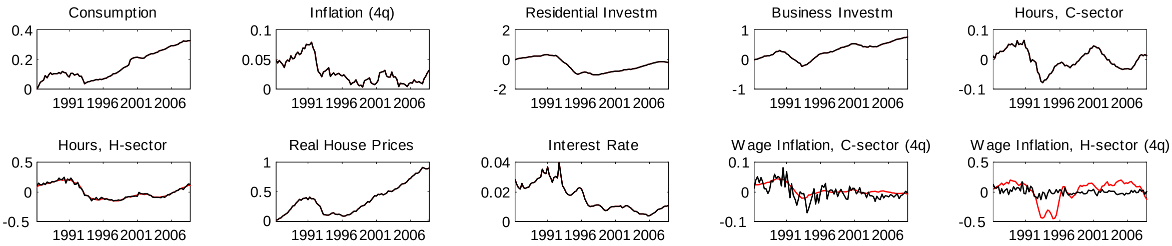

Figure 1. Matched data series (black) and smoothed variables (red), 1986q1-2008q3.

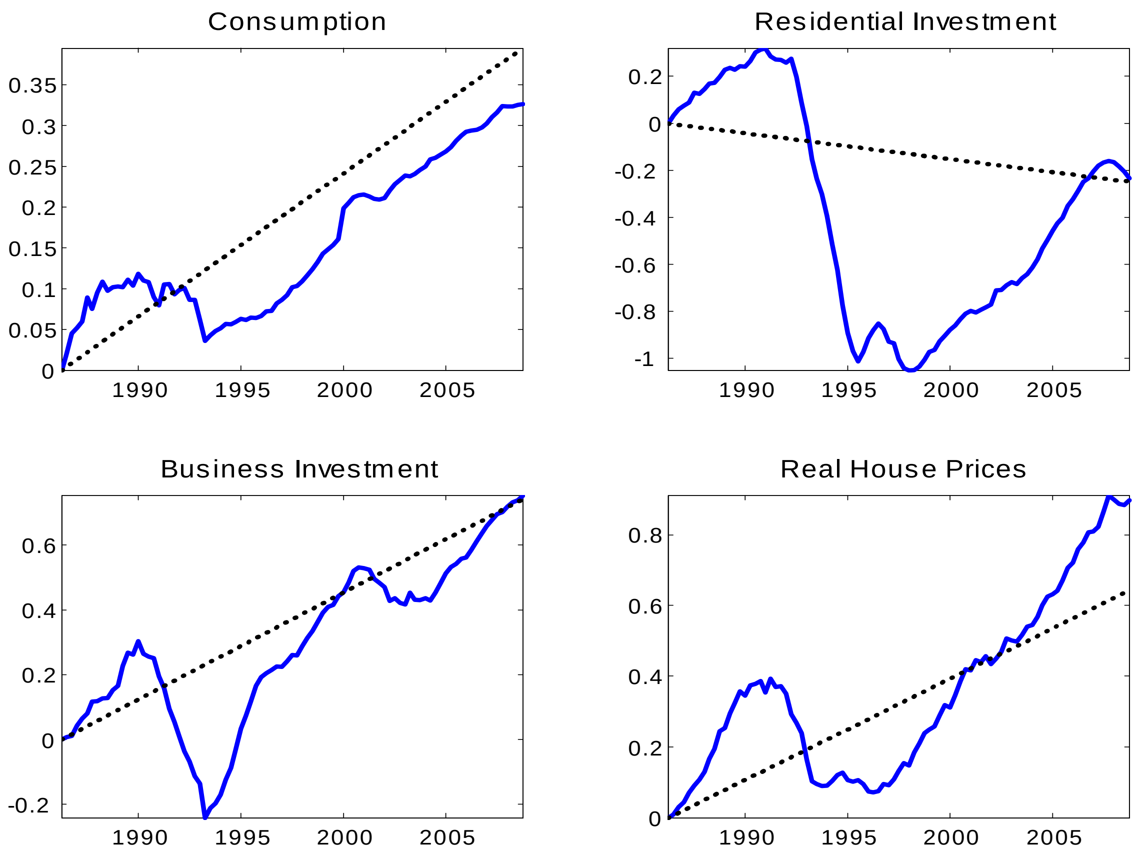

Figure 2. Selected data series 1986q1-2008q3 and estimated trends.

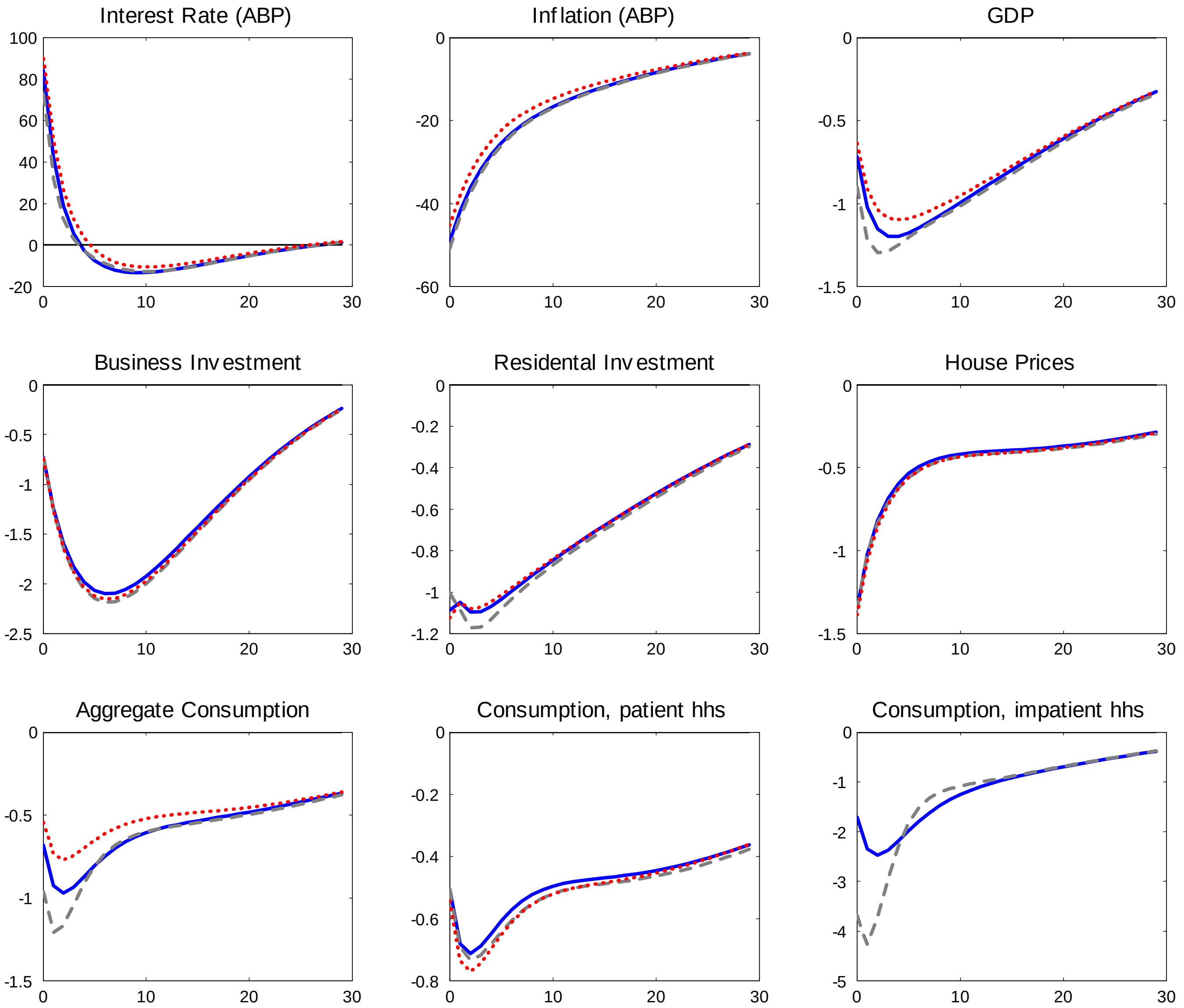

Figure 3. Impulse response functions to a monetary policy shock, $e_{r,t}$. Interest rate and inflation in annualized basis points (ABP), all other variables in percent deviation from steady state. Solid line shows benchmark calibration loan-to-value ratio $M = 0.85$, dashed line shows $M = 0.95$ and dotted line shows model without collateral constraints.

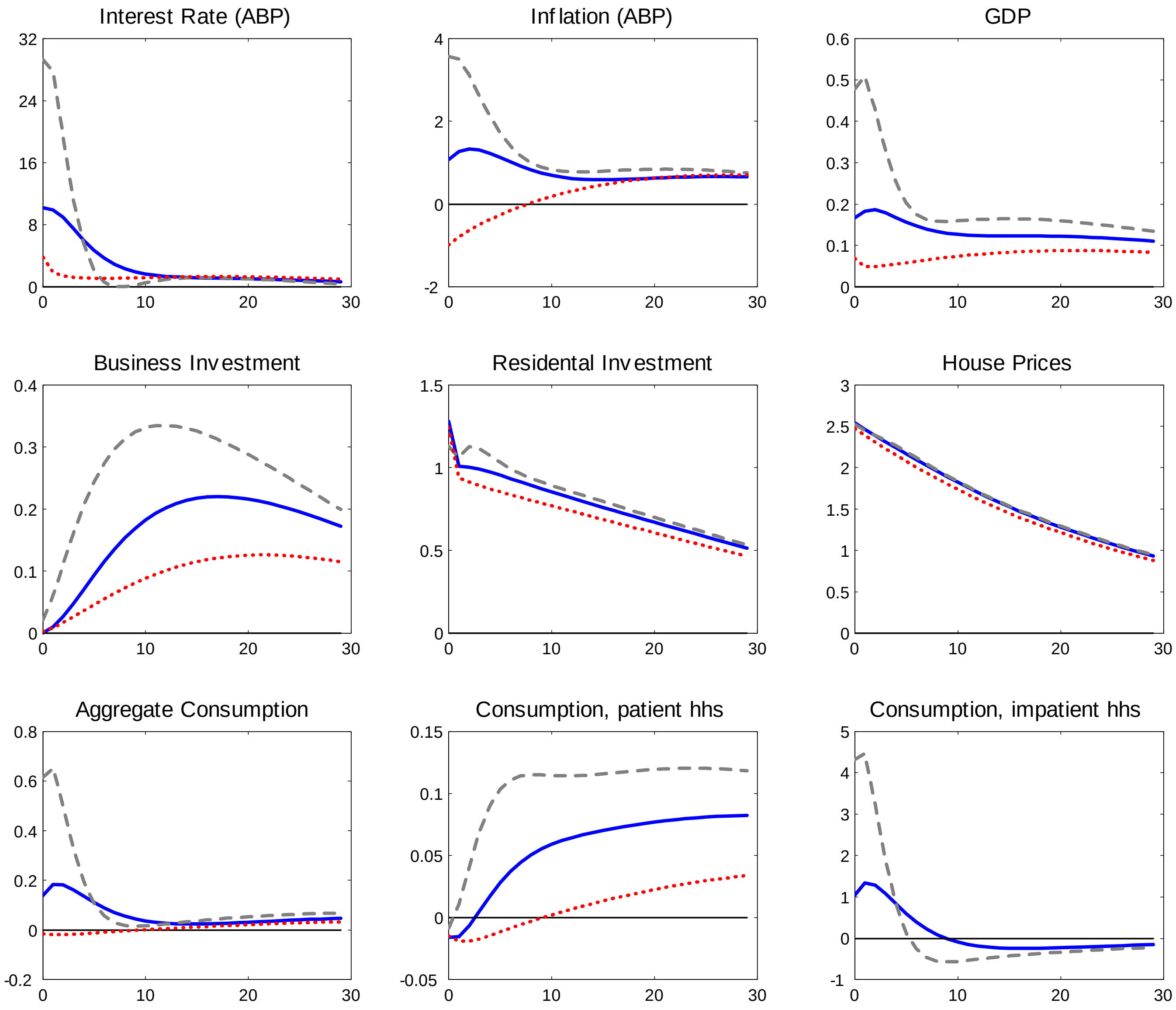

Figure 4. Impulse response functions to a housing preference shock, $e_{j,t}$. Plotting and scale details as in Figure 3.

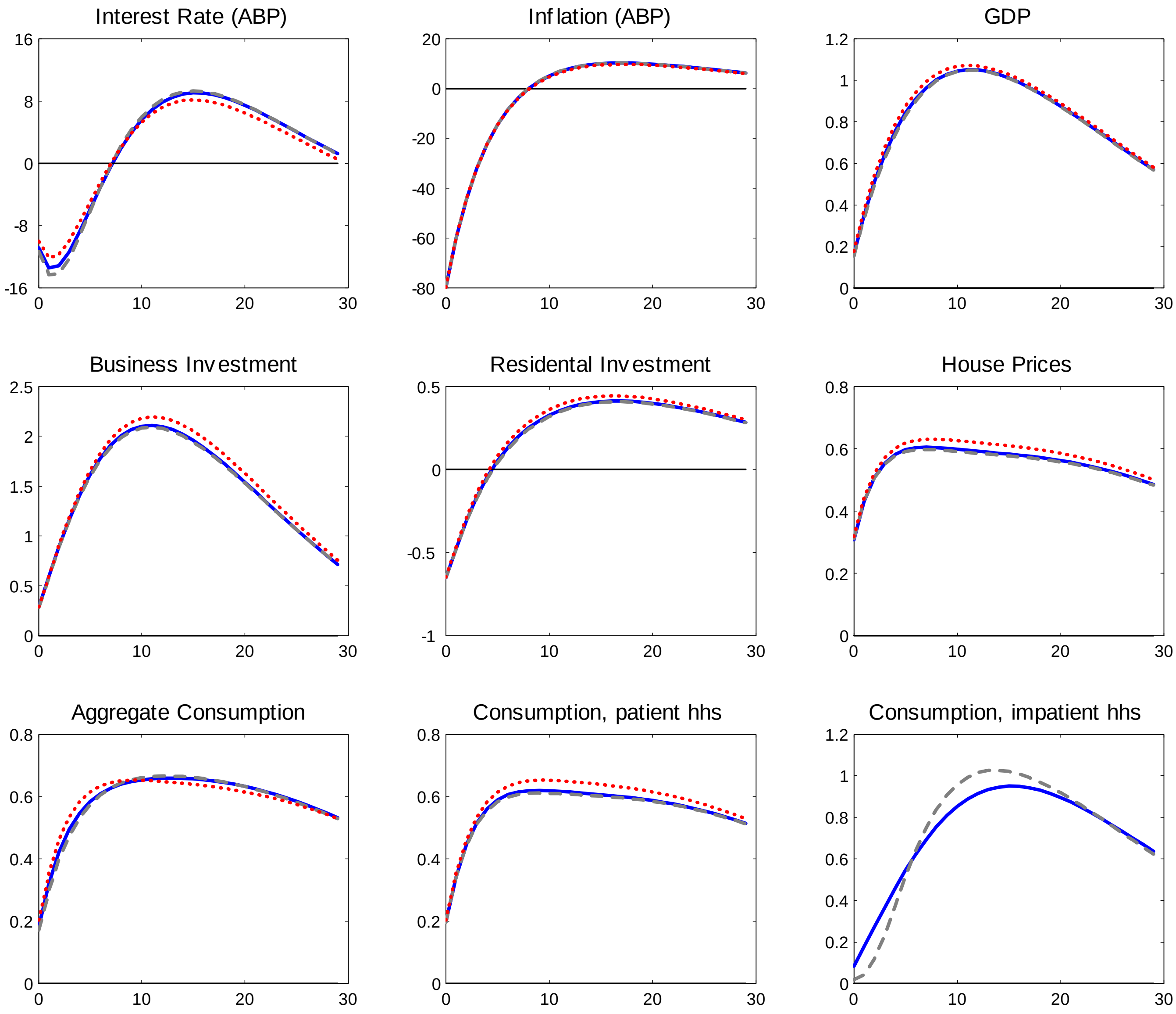

Figure 5. Impulse response functions to a consumption good technology shock, $e_{c,t}$. Plotting and scale details as in Figure 3.

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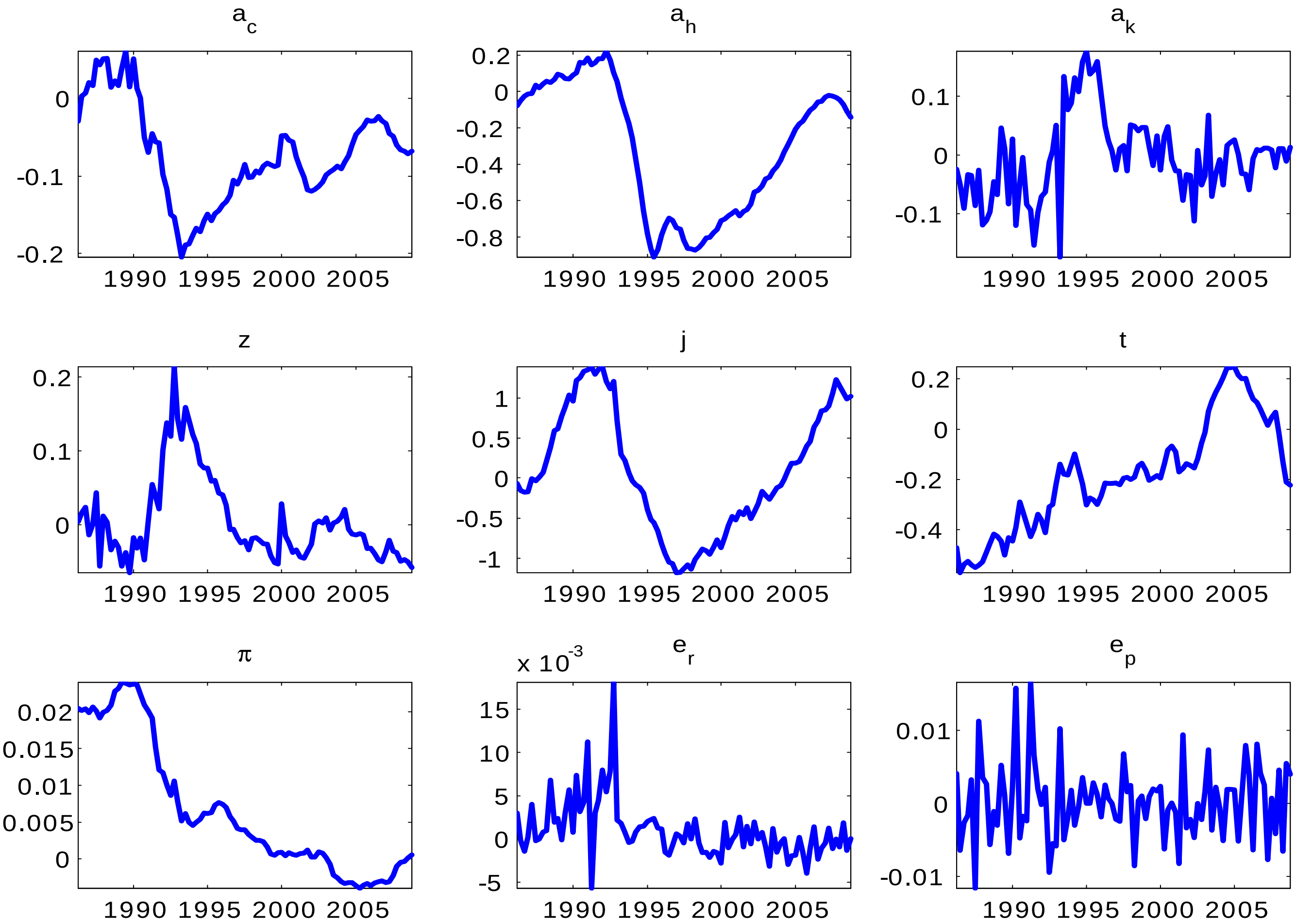

Figure 6. Smoothed exogenous shock processes.

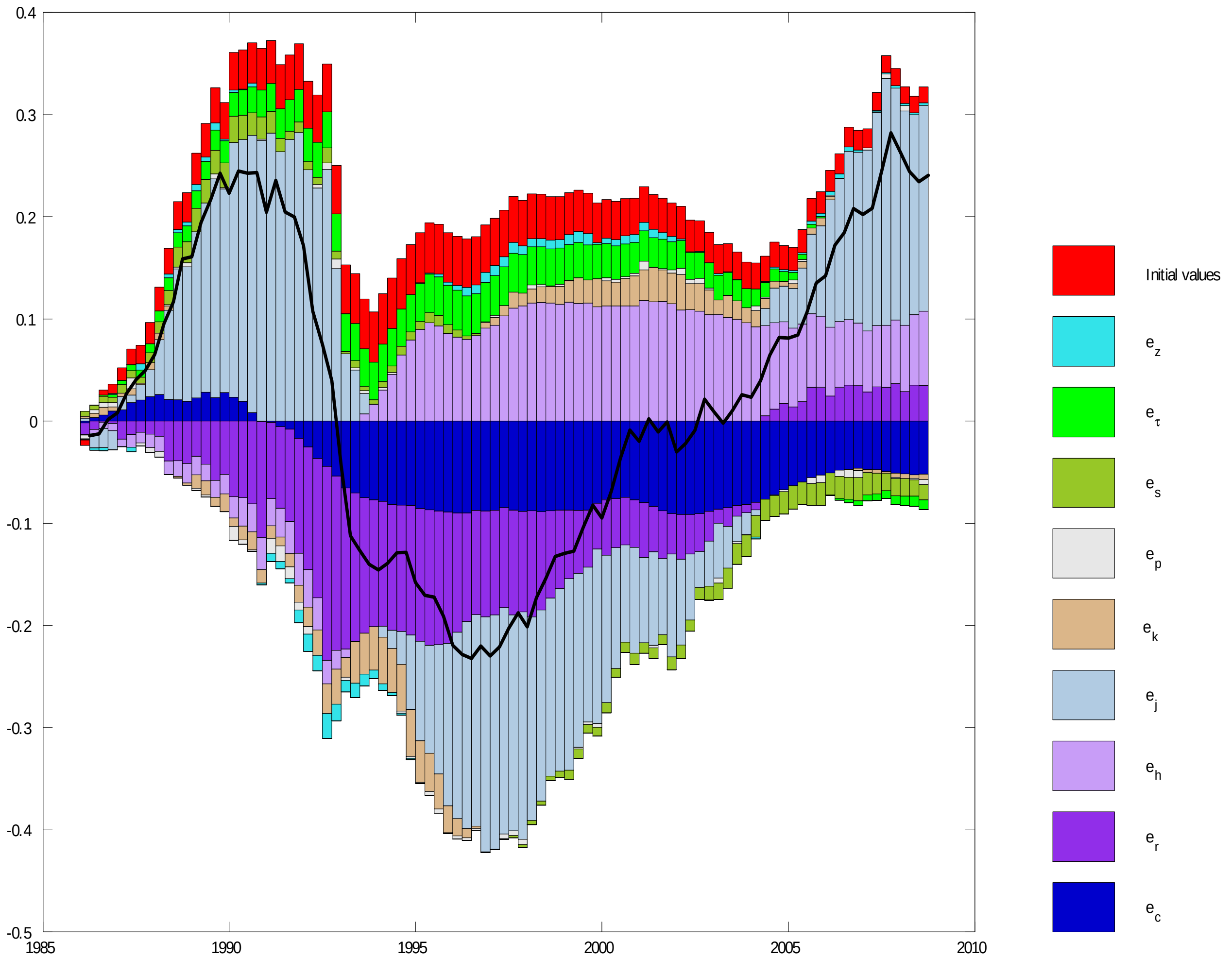

Figure 7. Historical shock decomposition for (detrended) real house prices q.

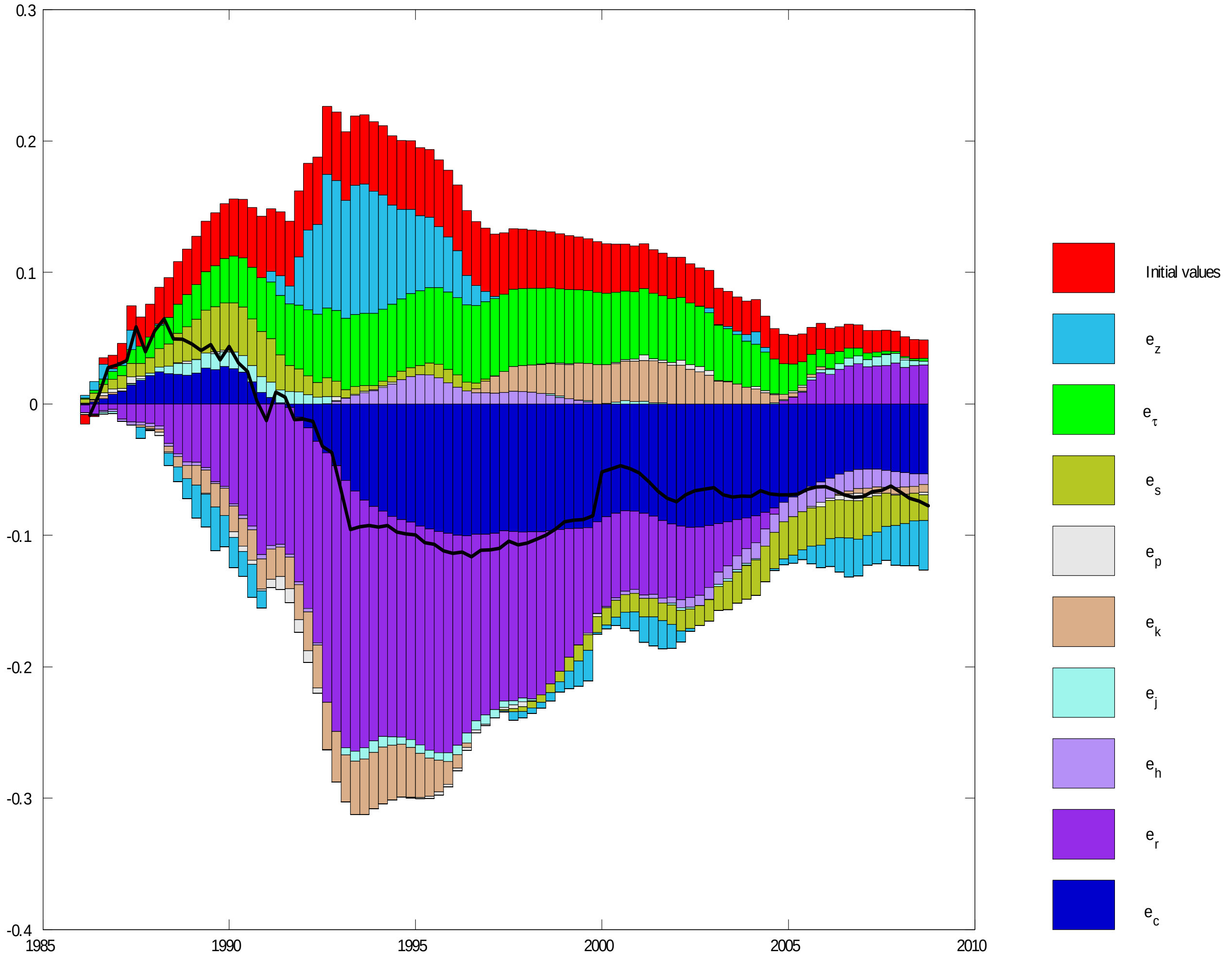

Figure 8. Historical shock decomposition for (detrended) aggregate consumption C.

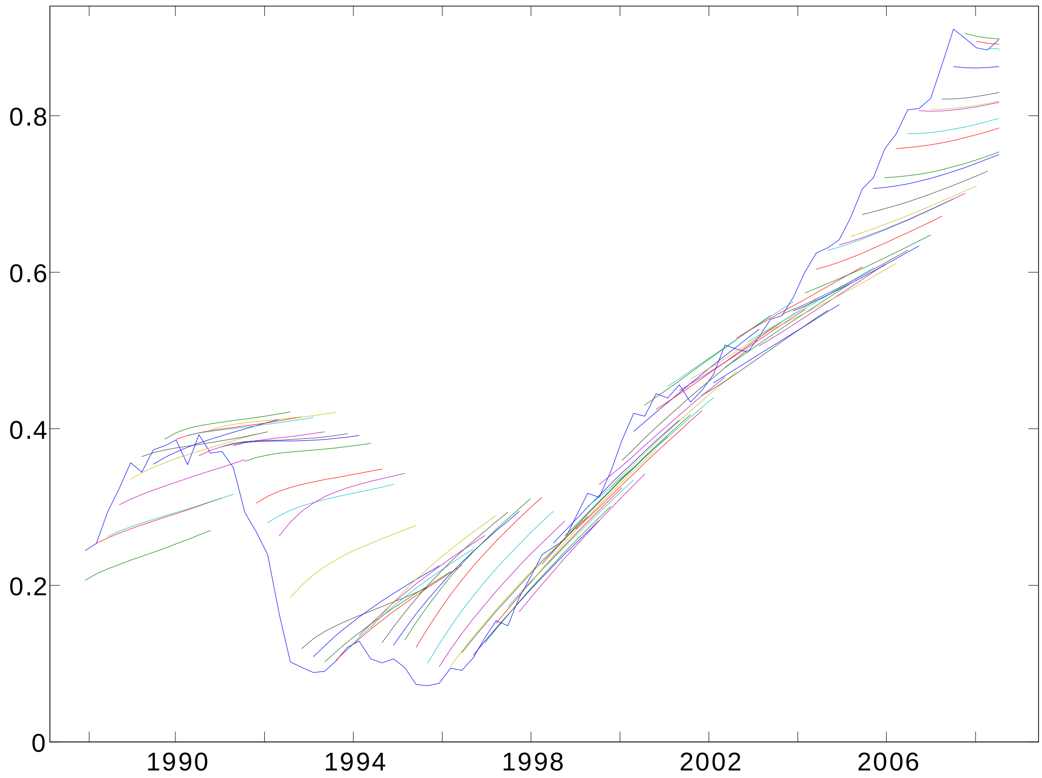

Figure 9. In-sample forecasts of real house price, q, 1988q3-2008q3.

A.2 Definition of investment adjustment cost function (Not for publication – online only)

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

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

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

where $\Gamma_{AK} = 1 + \gamma_{AK}$. This function implies zero investment adjustment costs in steady state.

A.3 Wage equations (Not for publication – online only)

The 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. $\omega_{it} = w_{it} - w_{it-1} + \pi_t$. $\varepsilon_{wc}, \varepsilon'_{wc}, \varepsilon_{wh}, \varepsilon'_{wh}$ are defined below.

A.4 Definitions of various parameters (Not for publication – online only)

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

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

A.5 Data appendix (Not for publication – online only)

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).