The Response of the Riksbank to House Prices in Sweden

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Abstract

In the aftermath of the recent financial crisis, an environment of historically low interest rates and extensive household indebtedness in the OECD countries have triggered a vivid debate on whether central banks should react to house price fluctuations in their pursuit of monetary policy. In Sweden, a period of low policy rates and house price inflation was halted when the central bank increased the interest rates in 2010. This paper studies whether the Riksbank reacted to house prices in 1993-2013. Using Bayesian methods and quarterly data, I estimate a DSGE model with patient and impatient households, where the central bank reacts to house price inflation. The results suggest that the Riksbank did respond to house prices during the sample period. The findings are robust and plausible from an economic point of view.

Keywords: House prices, monetary policy, DSGE models, Bayesian estimation

JEL codes: E31, E44, E52, E58
1 Introduction

Some of the most dramatic swings in economic history have coincided with changes in housing values, e.g., the Great Depression, the Japanese property crisis of the 90s, and the recent crisis. The determinants of the house price developments and its effects on overall economic activity is thus a hotly debated topic among researchers and policymakers. During the recent recession, house prices in some OECD countries dipped before rebounding strongly amid record low interest rates. In this context, concerns about a new property bubble refreshed the discussion of the policy implications for monetary authorities. Conventional monetary policy rules respond only to deviations in output and inflation. However, there is a growing debate on whether monetary policy should also respond to house price fluctuations directly, as opposed to indirectly through the ensuing effects on output.

This paper contributes to the ongoing debate on the relation between monetary policy and the development of house prices in Sweden. I investigate whether the central bank of Sweden, the Riksbank, responded to fluctuations in house prices 1993 - 2013. I estimate a Dynamic Stochastic General Equilibrium (DSGE) model using Bayesian methods on quarterly Swedish data. The results indicate that a response to house price inflation was a significant component of the Riksbank’s reaction function during the specified period.

The world’s major central banks keep reiterating that they do not target asset price inflation in general or house prices in particular. However, they do emphasise an opportunity to step in to curb a potential house price bubble. Published Minutes of the Riksbank Executive Board’s monetary policy meetings reveal that the board paid particular attention to the fluctuations of Swedish house prices. At the same time, the Board

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1 After large increases in the 1990s and the first half of the 2000s, house prices in most OECD countries followed one of two paths. While house prices in Denmark, Greece, the Netherlands, Portugal, Spain and the USA fell sharply, they depreciated minimally before firm rebounding in Australia, Belgium, Norway, Sweden and the UK amid historically low interest rates. Many observers pointed out that valuations appeared too high, and indicated that house price bubbles may have been built up in these economies, see e.g., Carney (2014), Zhu (2014) and OECD (2011).

2 See, e.g., Mankiw (2007) and Mishkin (2007) who review the idea of including house prices to the Taylor rule.
has recognized that the benchmark policy rate set by the Riksbank is a blunt and unsuitable instrument for responding to house price movements. A central bank’s tightening of monetary policy may prevent the build-up of an asset price bubble, but it can also have negative effects on the economy. Bernanke (2002) stresses that there are at least three reasons why monetary policy should not respond to asset prices per se, but rather to changes in the outlook for inflation and aggregate demand. First, there are no reasons to believe that central banks are better at identifying bubbles than markets. Monetary policy aimed at curbing unhealthy house price developments may thus hinder economic growth. Second, even if a bubble is identified, a mild contractionary monetary policy may accelerate a bubble while aggressive monetary policy can result in a sudden bursting of the bubble with long-lasting negative externalities similar to those during the Great Depression. Third, monetary policy tools cannot be directed towards a specific class of assets. Thus, monetary policy aimed to prick a bubble for just a fraction of assets, such as housing, would affect the prices of other assets as well.

Several papers have studied central banks’ reaction functions augmented with terms capturing responses to asset prices. For instance, Bernanke et al. (1999) augment the Taylor rule with the reaction to stock prices in a dynamic New-Keynesian framework. They find that the Federal Reserve did not respond to stock prices over the period 1979-1997. According to their results, the central Bank of Japan could have amplified the rise of stock price movements in the first half of the period (they report a highly significant coefficient in response to stock market returns of -0.286) and was attempting to stabilize the stock market in the period of 1989-1997 (the estimated reaction to stock returns is 0.188 and highly significant). Gilchrist and Leahy (2002) employ the model of Bernanke et al. (1999) and analyze whether central banks should response to stock prices. They suggest that monetary authorities should not respond directly to stock prices but rather aim to stabilize inflation. Iacoviello (2005) studies the optimal monetary policy of the Federal Reserve with and without responses to house prices in the reaction function in a DSGE model. The structural parameters are obtained using minimum-distance estimation for

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3 See, for example, Minutes of the Executive Board’s monetary policy meetings, the Riksbank, February 10, 2010 and April 19, 2010.
the impulse responses implied by the model and those generated by an unrestricted vector autoregression (VAR). Iacoviello (2005) finds a positive significant coefficient on house prices ranging from 0.1 to 0.15 for the quarterly U.S. data sample comprising the period 1974 - 2005. However, his results indicate that if the central bank’s aim is to minimize output and inflation fluctuations, the benefits of responding to house prices are minimal. Finocchiaro and Queijo von Heideken (2013) estimate the response of three central banks (the Federal Reserve, the Bank of England and the Bank of Japan) in a DSGE model using Bayesian methods. Their findings suggest that these central banks did react to house prices over the period 1983-2008 for the U.S. and the U.K. and 1970-1995 for Japan. The estimated coefficients on house price inflation are 0.36 for the U.S., 0.16 for the U.K. and 0.26 for Japan.

This study complements the existing literature in two respects. First, to the best of my knowledge, this is the first paper that investigates whether the Riksbank has responded to house prices in recent years. The paper is closely related to the aforementioned paper by Finocchiaro and Queijo von Heideken, but focuses on the Swedish setting in recent years. Second, this study supplements the scarce empirical literature on estimated DSGE models with monetary policy responses to house prices.

The remainder of the paper is organized as follows. Section 2 presents the model used for the estimation. Section 3 describes the data. Section 4 reviews the estimation methodology. Section 5 presents the main results of the paper. Section 6 concludes.

2 The model

The model used to address the central bank’s response to house prices belongs to a class of DSGE models. These setups have become a standard tool for monetary policy analysis because of their useful empirical properties (under plausible assumptions) and ability to address important monetary policy issues (Christiano et al., 2010). One of the very important features of DSGE models is the addition of frictions that allow monetary policy
to have real effects.

**Description of the model**

The model follows Iacoviello (2005) closely and assumes an economy populated by three types of agents: patient and impatient households, and entrepreneurs. The model assumes two types of households in order to introduce borrowing and lending within the household sector. Patient households value the future more than impatient households and thus have lower discount rates. Patient households borrow without limits. Impatient households are constrained in their borrowing by the value of housing that serves as a collateral. Debt contracts are set in nominal terms. Both types of households consume a final good, demand housing and work for entrepreneurs. Housing is fixed in the aggregate and used as a collateral by impatient households and entrepreneurs. Entrepreneurs consume the final good and produce an intermediate good according to a Cobb-Douglas production function. To produce the intermediate good entrepreneurs combine labor of both types of households, housing and capital. The source of nominal rigidities is retailers who adjust prices. Based on the assumption that adjusting prices is costly, only a fraction of retailers change their prices, implying that prices are sticky. Retailers buy the intermediate good and transform it to the final good. The final good is sold under monopolistic competition and the profits from sales are rebated to patient households. A monetary authority sets the policy rate according to a Taylor-type rule.

The source of business cycles is the agents’ reactions to exogenous shocks to the economy. For instance, a positive demand shock drives up consumer and house prices. Higher house prices and, consequently, higher collateral value thus increases the borrowing capacity of constrained agents. At the same time rising inflation deflates outstanding debt, since obligation contracts are set in nominal terms. These two forces encourage even higher spending and accelerate consumption. In the case of a negative demand shock, consumer and house prices drop. A decrease in house prices tightens borrowing capacity, and deflation expands outstanding debt in real terms. Hence, the effects of a negative demand shock are the opposite to those of a positive demand shock. A positive supply shock
works differently. A price mark-up shock leads to a decline in house prices and higher inflation. Lower house prices shrink the borrowing capacity of constrained agents and thereby have a negative effect on their consumption. On the other hand, higher inflation reduces outstanding debts in real terms and entails an increase in consumption.

**Patient households**

Patient households maximize lifetime utility subject to a budget constraint. Letting \( \prime \) denote patient households, lifetime utility is given by:

\[
E_0 \sum_{t=0}^{\infty} z_t \beta'^t \left( \ln c'_t + j_t \ln h'_t - \frac{(L'_t)'^t}{\eta'} \right),
\]

where \( z \) is a time preference shock, \( \beta' \) is a discount factor, \( c' \) denotes consumption, \( j \) is a housing preference shock, \( h' \) represents housing holdings, \( L' \) are hours of work and \( \eta \) denotes labor supply aversion.

The budget constraint is given by:

\[
c'_t + q_t (h'_t - h'_{t-1}) + \frac{R_{t-1}}{\pi_t} b'_{t-1} = b'_t + w'_t L'_t + F_t + T'_t,
\]

where \( q \) is the real housing price, \( R \) is the nominal interest rate, \( \pi \) denotes the gross inflation rate, \( b \) is the real debt, or borrowings, \( w' \) the real wage, \( F \) are profits received from the retailers \( T' \) are net transfers from the central bank. Assuming a price level \( P_t \) at time \( t \), the gross inflation rate at time \( t \) is \( \pi_t = P_t / P_{t-1} \), the real housing price at time \( t \) is \( q_t = Q_t / P_t \) and the real wage at time \( t \) is \( w_t = W'_t / P_t \). At time \( t \) households borrow an amount \( B'_t \) and repay interest \( R_{t-1} B'_{t-1} \) on the loan taken at time \( t - 1 \). In real terms a loan taken at time \( t \) is \( b'_t = B'_t / P_t \) and the interest payment is equal to \( R_{t-1} B'_{t-1} / P_t = R_{t-1} B'_{t-1} P_{t-1} / (P_t P_{t-1}) = R_{t-1} b'_{t-1} / \pi_t \).

**Impatient households**

Impatient households also maximize lifetime utility and are subject, not only to a budget
constraint, but also to a borrowing limit. They discount the future more heavily than
patient households so that the discount factor of impatient households is less than that of
patient households. Impatient households can only borrow a fraction of the value of the
housing they possess. Impatient households maximize lifetime utility:

$$E_0 \sum_{t=0}^{\infty} \beta''(\ln c''_t + j_t \ln h''_t - \frac{(L''_t)^{\eta''}}{\eta''}),$$

(3)

subject to a budget constraint that follows

$$c''_t + q_t(h''_t - h''_{t-1}) + \frac{R_{t-1}}{\pi_t} b''_{t-1} = b''_t + w''L''_t + T''_t,$$

(4)

and a borrowing constraint

$$b''_t \leq m''E_t(q_{t+1}h''_{t+1} \pi_{t+1}/R_t),$$

(5)

where the notation " now denotes impatient households. The rest of the notation is
the same as before so that impatient households’ discount factor is $\beta''$, they choose
consumption $c''$, own housing $h''$ and work $L''$ hours earning the real wage $w''$. At
time $t$ these households face the same real housing price $q_t$, inflation $\pi_t$, interest rate
$R_t$, time preference $z$ and housing preference $j$ shocks as patient households. However,
their loans are bounded by the expected value of the housing value in the next period
$E_t(Q_{t+1} + h''_t)/R_t$, and by the loan-to-value ratio $m$. At time $t$ this borrowing limit equals to
$B''_t = m''E_t(Q_{t+1}h''_t + R_t)$, which in real terms becomes $b''_t = B''_t/P_t = m''E_t(Q_{t+1}h''_t/R_t)$,

Entrepreneurs

Entrepreneurs consume the final good and maximize their lifetime utility. They produce
an intermediate good according to a Cobb-Douglas production function, combining la-
bor of patient and impatient households, housing and capital. Entrepreneurs face the
same borrowing constraint as impatient households. Entrepreneurs maximize their utility

\[4\text{The loan-to-value (LTV) ratio expresses the ratio of loans held using the real estate as security to}
\text{the total value of the real estate held.}\]
function

$$E_0 \sum_{t=0}^{\infty} z_t \gamma^t \ln c_t,$$  \hspace{1cm} (6)

subject to the following constraints:

$$Y_t = A_t K_t^\mu L_{t-1}^{\nu} (1-\mu-\nu)^{\alpha(1-\mu-\nu)}$$  \hspace{1cm} (7)

$$\frac{Y_t}{X_t} + b_t = c_t + q_t(h_t - h_{t-1}) + \frac{R_{t-1}}{\pi_t} b_{t-1} + w'_t L'_t + w''_t L''_t + I_t + \xi_{k,t},$$  \hspace{1cm} (8)

$$I_t = K_t - (1-\delta)K_{t-1},$$  \hspace{1cm} (9)

$$\xi_{k,t} = \psi \left( \frac{I_t}{K_{t-1}} - \delta \right) \frac{K_{t-1}}{2\delta},$$  \hspace{1cm} (10)

$$b_t \leq mE_t(q_{t+1}h_t \pi_{t+1}/R_t).$$  \hspace{1cm} (11)

As shown in equations (6) - (11), entrepreneurs discount the future at the rate $\gamma$ and face a time preference shock $z$, and a technology shock $A$. At time $t$ they produce an intermediate good $Y_t$, combining capital $K_t$, labor supply of patient households $L'_t$ and impatient households $L''_t$. The share of capital, housing and labor of patient and impatient households in the production function are respectively $\mu, \nu, \alpha$ and $(1-\alpha)$. The flows of funds at time $t$ are determined by entrepreneurs’ sales of produced goods at mark-up $X$, borrowing $b_t$, consumption $c_t$, a change of housing stock $q_t(h_t - h_{t-1})$, interest repayments in real terms $b_{t-1}R_{t-1}/\pi_t$, paying off the wages to patient households $w'_t L'_t$ and to impatient households $w''_t L''_t$ as well as investing $I_t$ with adjustment costs for capital installation $\xi_{k,t}$.

**Retailers**

Retailers purchase the intermediate good and costlessly transform it into the final good. A continuum of retailers $n$ aggregate the intermediate good $Y_t$ according to a Dixit-Stiglitz technology to produce the final good $Y_t^f$:

$$Y_t^f = \left[ \int_0^1 Y_t(n)^{\frac{1}{2}} dn \right]^{\frac{1}{2}},$$  \hspace{1cm} (12)
where $u_t$ is a measure of substitutability among the intermediate goods. The retail sector is characterized by monopolistic competition and prices are sticky. Specifically, a fraction $\theta$ (Calvo parameter) of prices stays unchanged, while a fraction $1-\theta$ of prices can be adjusted every period. Profits $F_t = (1 - 1/X_t)Y_t$ of sales are transferred to patient households. These assumptions define the New Keynesian Phillips Curve. The log-linearized version of the curve is given by:

$$\pi_t = \frac{1}{1 + \beta} \pi_{t-1} + \frac{\beta}{1 + \beta} \pi_{t+1} - \kappa X_t + e_{u,t}, \quad (13)$$

where $\kappa$ is the Phillips curve slope and $e_{u,t}$ is an inflation shock.

**Monetary policy**

A central bank is responsible for monetary policy. The monetary policy is implemented according to a Taylor-type interest rate rule:

$$R_t = \rho R_{t-1} + (1 - \rho)(r_\pi \pi_t + r_Y Y_t + r_q \Delta q) + e_{R,t} \quad (14)$$

At time $t$ the central bank sets a nominal interest rate $R_t$ as a function of the existing policy rate according to an interest rate smoothing component $\rho$, and responding to contemporaneous inflation $\pi_t$, output $Y_t$ and house price inflation $\Delta q_t$. A monetary shock is represented by $e_{R,t}$, and $r_\pi$, $r_Y$, $r_q$ are the coefficients on inflation, output and house price inflation, respectively.

**Shock structure**

There are five shocks in the model: housing preference, monetary, technology, time preference, and inflation shocks. Equations (14) - (16) become the housing-preference, technology and time-preference shocks, respectively. Monetary and inflation shocks ($e_{R,t}$ and $e_{u,t}$ respectively) are independent and identically distributed stochastic variables.

The housing preference shock is given by:

$$j_t = \rho_j j_{t-1} + e_{j,t}, \quad (15)$$
the technology shock is defined:

\[ A_t = \rho A_{t-1} + e_{A,t}, \tag{16} \]

and the time preference shock evolves according to:

\[ z_t = \rho z_{t-1} + e_{z,t}, \tag{17} \]

where \( \rho_j, \rho_A \) and \( \rho_z \) are coefficients, and \( e_{j,t}, e_{A,t} \) and \( e_{z,t} \) are independent and identically distributed variables.

**Equilibrium**

The model is in equilibrium when all the conditions specified above are satisfied and markets clear. The housing market clearing condition:

\[ 1 = h_t + h_t' + h_t'', \tag{18} \]

and the goods market clearing condition can be written:

\[ Y_t = c_t + c_t' + c_t'' + I_t, \tag{19} \]

and the loans market clears when:

\[ 0 = b_t + b_t' + b_t''. \tag{20} \]

**Log-linearization**

I solve this nonlinear model using a log-linear approximation technique. The equations describing the model are replaced by their first-order Taylor approximations around the steady state. The full set of log-linearized equations used for the estimation is reported in Appendix 2.
3 Data description

The data used for the estimation consists of series on real GDP, real consumption, the consumer price index (CPIX), real house prices and the nominal interest rate. All the series cover the period 1993Q1 - 2013Q4. This period is chosen in order to avoid the turbulence caused by the switch from a fixed to floating exchange rate in Sweden in 1992.\(^5\)

The data on real GDP and real consumption (total final consumption expenditure of households) on a quarterly basis with reference year of 2013, are obtained from Statistics Sweden.\(^6\) The data series correspond, respectively, to the real output and real aggregate consumption variables in the model.

The data on the consumer price index (CPIX) on a monthly basis are obtained from the Riksbank and have been converted to quarterly observations. The quarterly data values are the average values of the first three months of each quarter. One-quarter differences of the series correspond to the inflation variable in the model.

Quarterly data on house prices (a real-estate price index for one- and two-dwelling buildings for permanent living) are also from Statistics Sweden. The series is deflated with CPIX and corresponds to real house prices in the model.

Data on nominal interest rates (returns on Swedish Treasury Bills with 3 months maturity rate, quarterly averages) are obtained from the Riksbank. The series has been converted to quarterly units and corresponds to the nominal interest rate in the model.

Before I estimate the model, I adjust for seasonality and linearly detrend the series.

\(^5\)When the Riksbank abandoned the fixed exchange rate against the ECU (European Currency Unit) in 1992, the krona depreciated sharply against other currencies. The depreciation of the krona and changes in indirect taxes generated inflationary impulses. In 1993 the Riksbank declared that the objective of monetary policy would be to achieve price stability, and an explicit inflation target was implemented in 1995.

\(^6\)Statistics Sweden (Statistiska Centralbyrån).
The seasonally adjusted data series are shown in Figure 1, Appendix 1; and the autocorrelations and cross-correlations of the selected series are presented in Table 1. The first-order correlation coefficients (0.94 for consumption, 0.98 for house prices and 0.88 for output) suggest that the series are very persistent. Co-movement of output with house prices and consumption can be detected by the measure of correlation coefficient between the series. The reported contemporaneous correlations (0.84 for consumption, 0.75 for house prices) are high. This indicates that the consumption and house prices capture the main pattern of co-movement with GDP over the period. The interpretation provided by the model framework of the positive correlation between consumption and house prices is that a rise of house prices increases the borrowing capacity of agents and allows for a higher consumption.

### Table 1: The autocorrelations and cross-correlations: house prices, consumption and GDP

<table>
<thead>
<tr>
<th></th>
<th>GDP</th>
<th>Consumption</th>
<th>House price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autocorrelation</td>
<td>0.88</td>
<td>0.94</td>
<td>0.98</td>
</tr>
<tr>
<td>Correlation with GDP</td>
<td>1.00</td>
<td>0.84</td>
<td>0.75</td>
</tr>
</tbody>
</table>

4 Estimation

The Bayesian approach used in this study has become a standard way to estimate DSGE models. The crucial difference from other methods of estimation is that Bayesian econometrics makes use of pre-sample information. For instance, microeconometric evidence can provide priors for specific model parameters. Applying Bayesian methods, the model parameters are then estimated conditional on priors. This technique has proved to be particularly useful given the short time series often available and the large number of parameters commonly specified in DSGE models.

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7 The data series are seasonally adjusted according to X-12-ARIMA program with software package Gretl 4.6.5.
8 There exists a variety of alternatives to Bayesian estimation (e.g., Generalized Method of Moments, Minimum-distance estimation that minimizes the discrepancy between VAR and DSGE impulse responses, Maximum likelihood estimation). There is a large literature documenting the optimality properties of Bayesian inference decision procedures, see, for instance, Schorfheide (2000), Lubik and Schorfheide (2003), Fernandez-Villaverde and Rubio-Ramirez (2004), Rabanal and Rubio-Ramirez (2005).
Estimation strategy
I estimate two versions of the model on Swedish quarterly data over the period 1993Q1 through 2013Q4 using the software package Dynare 4.4.3. In the first version of the model, the Taylor rule is augmented with a variable gauging the central bank’s reaction to house price inflation (the unrestricted model):

$$R_t = \rho R_{t-1} + (1 - \rho)(r_t \pi_t + r_Y Y_t + r_q \Delta q) + \epsilon_{R,t}; \quad (21)$$

In the second (restricted) model, the reaction to house price inflation is set to zero:

$$R_t = \rho R_{t-1} + (1 - \rho)(r_t \pi_t + r_Y Y_t) + \epsilon_{R,t}. \quad (22)$$

The Bayesian estimation is made applying the Kalman filter and Markov Chain Monte Carlo (MCMC) simulations using the Metropolis-Hasting (MH) algorithm. To obtain posterior distributions I simulate 5 chains with 100 000 replications each for MH-algorithm. The calibration of parameters and setting of prior distributions is made using information from the previous studies described below. The two (restricted and unrestricted) models are compared based on their posterior odds ratio.  

Calibrated parameters
Some of the parameters are calibrated since they cannot be identified without information on other variables. I follow Finocchiaro and Queijo von Heideken (2013) by assigning the values given to the discount factors, capital and housing shares in the production function and the capital depreciation rate. The discount rate for patient households set to 0.9925. This indicates that the annual interest rate is equal to 3 per cent at steady state. The discount rate for impatient households is calibrated to 0.97. The discount rate for entrepreneurs is based on a firm’s internal rate of return and set to 0.98. The shares of capital and housing in the production function are set to 0.35 and 0.035 respectively. The depreciation rate of capital is assigned the value of 0.03 implying a steady-state depre-

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9To compare two alternative models the rule of thumb presented in Kass and Raftery (1995) is commonly used.
10The values are virtually the same as in Iacoviello and Neri (2009) and Sellin and Walentin (2010).
cation rate of 12 per cent annually. The probability of not adjusting prices (the Calvo parameter) is set to 0.7, implying that prices stay fixed for about 10 months. The wage income share of the patient households is set to 0.64.

The values of parameters not defined in Finocchiaro and Queijo von Heideken (2013), I assign the values from a similar study of Iacoviello and Neri (2009). The weight on housing relative to consumption in the utility function is set to 0.1; the gross markup is fixed to 1.15 and corresponds to a steady-state mark-up of 15 per cent. The loan to value (LTV) ratios for impatient households and entrepreneurs are restricted to 0.85 so that the value of a loan is 85 per cent of the collateral. While Iacoviello (2005) fixes the LTV ratio for impatient households at the rate of 0.55, Finocchiaro and Queijo von Heideken (2013) estimate the parameter and find it to be higher (0.73 - 0.81); Iacoviello (2009) assumes that the ratio equals 0.85. When estimating their model on Swedish data, Sellin and Walentin (2010) fix the ratio to 0.85 and explain that in Sweden for the sample period 1986-2008 this ratio was plausibly increasing over time, but there is no high quality data on quarterly basis. The calibrated parameters are summarized below in Table 2.

<table>
<thead>
<tr>
<th>Parameter Value Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta'$ 0.9925 $\beta''$ 0.97</td>
</tr>
</tbody>
</table>

Prior distributions

I use the prior distributions proposed by Finocchiaro and Queijo von Heideken (2013). The distributions of the autoregressive coefficients of the shock processes are assumed to follow beta distributions with mean 0.85 and standard deviation 0.05. Regarding the parameters of the Taylor rule, the long run coefficient on inflation and output are described by a gamma distribution with mean 1.8 and 0.125, and standard errors 0.4 and 0.1, respectively. The persistence coefficient of the interest rate smoothing component

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is beta-distributed and is centered at 0.7 with a standard error of 0.1. The prior for the elasticity of labor supply follows a normal distribution with mean 2 and a standard deviation 0.75. The capital adjustment cost prior is set to be gamma-distributed with mean 2 and standard error 1. The coefficient on house-price inflation is assumed to be a relatively uninformative prior with mean 0 and standard deviation 0.5. Such a restriction is in line with the aim of the model testing when the significance of the coefficient should be revealed.

5 Estimation results

This section presents the main estimation results. In the first part I present and discuss the posterior estimates. Variance decomposition and impulse response functions (IRFs) are analyzed in the second part. The comparison of the models and the results of various robustness tests are discussed in the third part of the section.

Posterior distributions

The obtained 5, 50 and 95 percentiles of the posterior distribution for the estimated structural parameters are displayed in Table 3, together with their statistics for the prior distribution. Prior and posterior densities for the restricted and unrestricted models are displayed in Figure 2, Appendix 1. Generally, the results of the estimation are consistent with those of Finocchiaro and Queijo von Heideken (2013) and other previous studies. The estimated parameter values are similar for the restricted and unrestricted models, and plausible from an economic point of view.

The estimates of the parameters in the exogenous shock processes range between 0.80 and 0.96, indicating high persistence of the shock processes.

The degree of interest rate smoothing is relatively high for both the restricted and unrestricted models; the estimates are equal to 0.87 and 0.88 respectively in the models where the monetary authority does and does not respond to house prices. These high rates of
Table 3: Estimated parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
<th>Mean</th>
<th>SD</th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
<th>5%</th>
<th>50%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_q$</td>
<td>normal</td>
<td>0</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.1282</td>
<td>0.3172</td>
<td>0.5145</td>
</tr>
<tr>
<td>$\rho$</td>
<td>beta</td>
<td>0.7</td>
<td>0.1</td>
<td>0.8381</td>
<td>0.8708</td>
<td>0.9043</td>
<td>0.8495</td>
<td>0.8795</td>
<td>0.9121</td>
</tr>
<tr>
<td>$r_{\pi}$</td>
<td>gamma</td>
<td>1.8</td>
<td>0.4</td>
<td>2.396</td>
<td>2.979</td>
<td>3.5453</td>
<td>2.5013</td>
<td>3.1821</td>
<td>3.77</td>
</tr>
<tr>
<td>$r_{\psi}$</td>
<td>gamma</td>
<td>0.125</td>
<td>0.1</td>
<td>0.0459</td>
<td>0.107</td>
<td>0.1695</td>
<td>0.0173</td>
<td>0.0861</td>
<td>0.1449</td>
</tr>
<tr>
<td>$\psi$</td>
<td>gamma</td>
<td>2</td>
<td>1</td>
<td>2.7524</td>
<td>4.3933</td>
<td>5.9446</td>
<td>2.735</td>
<td>4.3896</td>
<td>6.3718</td>
</tr>
<tr>
<td>$\eta$</td>
<td>normal</td>
<td>2</td>
<td>0.75</td>
<td>4.3825</td>
<td>5.341</td>
<td>6.4014</td>
<td>4.2492</td>
<td>5.2287</td>
<td>6.2931</td>
</tr>
<tr>
<td>$\rho_j$</td>
<td>bet</td>
<td>0.85</td>
<td>0.1</td>
<td>0.9306</td>
<td>0.9604</td>
<td>0.992</td>
<td>0.929</td>
<td>0.9579</td>
<td>0.9992</td>
</tr>
<tr>
<td>$\rho_{e}$</td>
<td>bet</td>
<td>0.85</td>
<td>0.1</td>
<td>0.8181</td>
<td>0.8677</td>
<td>0.9186</td>
<td>0.808</td>
<td>0.8602</td>
<td>0.9135</td>
</tr>
<tr>
<td>$\rho_{z}$</td>
<td>bet</td>
<td>0.85</td>
<td>0.1</td>
<td>0.7632</td>
<td>0.8021</td>
<td>0.8425</td>
<td>0.7547</td>
<td>0.8002</td>
<td>0.8431</td>
</tr>
<tr>
<td>$\hat{e}_{z}$</td>
<td>gamma</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0325</td>
<td>0.0383</td>
<td>0.0442</td>
<td>0.0323</td>
<td>0.0385</td>
<td>0.0442</td>
</tr>
<tr>
<td>$\hat{e}_{A}$</td>
<td>gamma</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0249</td>
<td>0.0299</td>
<td>0.0349</td>
<td>0.0248</td>
<td>0.03</td>
<td>0.036</td>
</tr>
<tr>
<td>$\hat{e}_{u}$</td>
<td>gamma</td>
<td>0.05</td>
<td>0.05</td>
<td>0.018</td>
<td>0.0207</td>
<td>0.0235</td>
<td>0.0177</td>
<td>0.0205</td>
<td>0.0232</td>
</tr>
<tr>
<td>$\hat{e}_{\eta}$</td>
<td>gamma</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0494</td>
<td>0.1334</td>
<td>0.2132</td>
<td>0.0497</td>
<td>0.1392</td>
<td>0.2305</td>
</tr>
<tr>
<td>$\hat{e}_{R}$</td>
<td>gamma</td>
<td>0.05</td>
<td>0.05</td>
<td>0.0013</td>
<td>0.0016</td>
<td>0.0018</td>
<td>0.0013</td>
<td>0.0016</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

Column 1 - 4 display parameters estimated and their prior distributions. Column 5 - 7 provide the obtained 5, 50 and 95 percentiles for the estimated parameters of the restricted model, Columns 8 - 10 - for the unrestricted model.

Smoothing components imply that the central bank only gradually moves towards the policy prescribed by responding to only output and inflation. The estimated mean reaction of the monetary authority to output is around 0.10 in both models. Studying Swedish data 1986Q1-2008Q3, Walentin and Sellin (2010) estimate the reaction to the output gap at 0.15 and find that the data is uninformative about the Taylor-rule parameter for responding to inflation. In line with Finocchiaro and Queijo von Heideken (2013), the estimated mean reaction to inflation of 3.18 is higher in the benchmark model than in the model where the interest rate is insensitive to house price inflation (mean estimate is equal to 2.98). While the estimated parameter of the central bank’s reaction to output is modest, the estimated reaction to inflation is among the highest values documented in the literature.\(^{11}\) This result suggests that the Riksbank has been aggressive in targeting inflation.

The estimate of the central bank response to house price inflation of 0.32 is fairly close to the coefficients found by Finocchiaro and Queijo von Heideken (2013): 0.36 for the

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\(^{11}\)See, for instance, Smets and Wouters (2007), Onatski and Williams (2010).
US, 0.16 for the UK and 0.26 for Japan. However, the discrepancies of the estimates for the parameter of capital adjustment cost and labor supply elasticity warrant discussion. Although the mean estimates for the parameter of capital adjustment cost (estimated at 4.39 in the unrestricted and restricted models) and parameter of labor supply elasticity (estimated at 5.34 and 5.23 in the unrestricted and restricted models respectively) are higher than those reported by Finocchiaro and Queijo von Heideken (2013), the values are in line with the other studies that suggest a parameter of capital adjustment cost between 2.8 and 10, and that of the labor supply elasticity between 1 and 6.\textsuperscript{12}

**Variance decomposition**

Variance decomposition shows how much of the forecast error variance of the variable is explained by exogenous shocks to the other variables. The variance decomposition assuming an infinite horizon is presented below in Table 4 for the unrestricted (preferred) model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>( \hat{\epsilon}_j )</th>
<th>( \hat{\epsilon}_u )</th>
<th>( \hat{\epsilon}_A )</th>
<th>( \hat{\epsilon}_R )</th>
<th>( \hat{\epsilon}_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>House price</td>
<td>48.76</td>
<td>4.28</td>
<td>29.65</td>
<td>0.25</td>
<td>17.06</td>
</tr>
<tr>
<td>Inflation</td>
<td>3.95</td>
<td>35.96</td>
<td>30.93</td>
<td>6.69</td>
<td>22.47</td>
</tr>
<tr>
<td>Nominal interest rate</td>
<td>9.62</td>
<td>15.22</td>
<td>43.08</td>
<td>0.86</td>
<td>31.23</td>
</tr>
<tr>
<td>Output</td>
<td>1.59</td>
<td>17.94</td>
<td>78.35</td>
<td>0.55</td>
<td>1.57</td>
</tr>
<tr>
<td>Consumption, patient households</td>
<td>7.9</td>
<td>16.48</td>
<td>63.29</td>
<td>0.93</td>
<td>11.39</td>
</tr>
<tr>
<td>Consumption, impatient households</td>
<td>4.3</td>
<td>51.7</td>
<td>35.99</td>
<td>1.82</td>
<td>6.2</td>
</tr>
<tr>
<td>Aggregate consumption</td>
<td>6.78</td>
<td>35.43</td>
<td>55.78</td>
<td>1.25</td>
<td>0.76</td>
</tr>
</tbody>
</table>

I continue with the description of variance decomposition of other variables with respect to the housing preference shock. According to the results, housing shocks mainly drive the movements of house prices and amount to 48.76 per cent of the total house-price variance. Technology shocks account for 29.65 per cent of the movements in house prices. This is an indicator of the connection between the housing sector and the rest of the economy. The time preference shock explains 17.06 per cent of the variation in the house prices. The monetary policy shock, however, appears to be unimportant for house price fluctuations.

\textsuperscript{12}See, for instance, Smets and Wouters (2003), Onatski and Williams (2010), Amisano and Tristani (2008), King and Rebelo (2000).
It can only explain 0.25 per cent of the variation in house prices.

The housing preference shock explains only a fraction of 1.59 per cent of the variance of output, whereas it is a significant component of the deviations of interest rates and aggregate consumption. 9.62 per cent of variability in the interest rates and 6.78 per cent of variability in aggregate consumption are accounted for by the housing preference shock.

**Impulse response functions**

The impulse responses (IRFs) are displayed below in Figure 1 and show how the transmission mechanism works both in the restricted and unrestricted models. The IRFs of house price levels, inflation, the nominal interest rate, output, aggregate consumption, consumption of patient and impatient households variables are plotted for monetary, housing-preference and technology shocks. Interestingly, the quantitative and qualitative features of the IRFs are similar under the two assumptions. In response to the shocks the variables keep the same direction and follow the same dynamic pattern.

**Monetary shock**

Initially in response to a contraction in monetary policy, consumption of impatient, or collateral-constrained, households significantly decrease, while consumption of patient households slightly increases. This can be explained by an income effect - constrained households are to repay their loans at higher interest rates whereas savers acquire higher returns on their investments. Overall, aggregate consumption decreases and consequently pulls down aggregate demand and inflation. House prices, however, remain stable. To counteract a drop in output and inflation, the monetary authority cuts the interest rate in the next period (quarter) and thereby stimulates the consumption of impatient households and causes a rise in house prices. Thereafter, inflation stabilizes and the real interest rate goes back to the steady state. Consequently, house prices, consumption of both types of households, and aggregate consumption return to their steady state levels. However, the effect of the monetary shock on output seems to be persistent, although the negative gap
Figure 1: Impulse response functions. Solid black lines show IRFs for the model where the central bank responds to house price inflation, dashed blue lines show IRFs for the model with no response to house prices.
between its level after 20 periods and its steady state is quite small. The response of the monetary authority to house-price inflation is suppressed by its reverse tactic (operations) to rebound output and inflation, and therefore, does not generate any visible effects on the development of the variables.

**Housing preference shock**

In this model, a housing preference shock changes the agents’ preferences for consumption and housing in their utility function. A positive housing preference shock stimulates demand for housing and leads to a rise in house prices. Higher value of housing increases the borrowing capacity of the debtors who use it as collateral. This, in turn, allows higher spending and drives up consumer prices and correspondingly inflation. The inflation initially overwhelms a nominal interest rate. On the one hand, this benefits impatient households whose outstanding debt is deflated. On the other hand, it deprives savers who suffer from deflation of their wealth. Thus, initially, patient households decrease their consumption while impatient households expand their consumption. Aggregate consumption and output are up. The monetary authority responds to the increase in output, inflation and house prices, and raises the nominal interest rate. In response to the higher interest rate, borrowers face a higher burden of outstanding debt. Therefore, new borrowing against higher-valued collateral (housing) is suppressed by the effect of higher interest repayments. This leads to a fall in consumption of collateral-constrained households. Patient households, or savers, conversely, enjoy the hike in interest rates as this enables them to increase their consumption. Aggregate consumption declines and drags down output and inflation. Notably, house prices do not converge to the steady state. They are very persistent and remain higher than at their initial level. After 20 periods, consumption of impatient households and output are lower than at their initial levels but consumption of patient households is higher than at its steady state.

**Technology shock**

Following a technology shock, inflation drops, and house prices go up. In this situation collateral-constrained agents benefit from the rise in house prices allowing more borrow-
ing. However, the decline in inflation increases the outstanding debt of borrowers in real terms. The effect of house price rises dominates initially and boosts the consumption of impatient households. Patient households are better off under higher real interest rates and increase their consumption. Aggregate consumption increases as well. The monetary authority chooses its policy considering deviations of inflation and output in opposite directions. Inflation reverts to its steady state level sustained by the increase of aggregate consumption. Followed by the serial improvement of interest rates, the rest of the variables converge to the steady state.

Model comparison and robustness

To investigate whether the Riksbank has responded to house prices I perform an exercise in model comparison. In the unrestricted (benchmark) model, the central bank is allowed to react to house price inflation. In contrast, the restricted (alternative) model features an interest rate policy that is insensitive to house price inflation (Specification 1). The examination of models is based on the evaluation of computed posterior odds ratios, which are reported below in Table 5 together with the estimated log marginal data density for every model.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unrestricted model, log marginal density</td>
<td>1192.26</td>
<td>1165.2</td>
<td>895.31</td>
<td>1074.32</td>
</tr>
<tr>
<td>Restricted model, log marginal density</td>
<td>1189.35</td>
<td>1163.82</td>
<td>892.39</td>
<td>1070.25</td>
</tr>
<tr>
<td>Posterior odds ratio</td>
<td>18.36</td>
<td>3.98</td>
<td>18.48</td>
<td>58.57</td>
</tr>
</tbody>
</table>


The posterior odds ratio of 18.36 favours the benchmark model. This suggests that the Riksbank did respond to house price inflation by setting a higher interest rate.

To verify the estimation results, I conduct a range of robustness tests. First, following Iacoviello (2005), I estimate the model with a Taylor rule determined by the monetary authority reaction to past inflation and past output, a backward-looking Taylor rule
(Specification 2):

\[ R_t = \rho R_{t-1} + (1 - \rho) \left( r_{\pi_t} \pi_{t-1} + r_Y Y_{t-1} + r_q \Delta q \right) + e_{R,t}. \] 

(23)

Second, I estimate the original model on the same data series but over the period from 1995Q1 - 2013Q4 (Specification 3). The reason for that is that the Riksbank introduced an inflation target of 2 per cent in 1995. Third, I estimate the benchmark model over the period from 1993Q1 - 2008Q1 (Specification 4) to study the importance of including the recent crisis.

The results of the robustness tests are reported above in Table 5 and include log marginal data density for every model and posterior odds ratios under the null hypothesis that the unrestricted model is preferred to the restricted one. The posterior odds ratios for all three tests are greater than the critical value shown in the rule of thumb for model comparison, and thus lend support to the estimation of the original models.

6 Conclusions

House prices in Sweden have undergone a substantial increase since the late 1990s. The recent recession is associated with a dramatic decline in house prices in most OECD countries. House prices in Sweden, however, depreciated only moderately in 2008-2009Q1 and subsequently rose amid low interest rates. In 2010-2011, the Riksbank tightened monetary policy, which temporarily curbed house price inflation. Following the Riksbank’s gradual lowering of its policy rate 2012-2013, house prices again started to increase. In light of these developments, the debate on whether the Riksbank responded to house prices, and, if so, if they were right to do so, has intensified.

In order to investigate whether the Riksbank reacted to house prices, I estimate a DSGE model where the monetary authority reacts to house price inflation. I rely on the basic model of Iacoviello (2005) and extend it by a time preference shock. The key feature of the model is liquidity-constrained agents who borrow in nominal terms using housing as
collateral. The assumption of nominal debt comes from the widespread practice of low-inflation countries to set debt contracts in nominal terms. The model is estimated using Bayesian methods on quarterly Swedish data 1993 - 2013. This study adds to the scarce empirical literature on estimated DSGE models featuring house price developments. The estimation results are robust, plausible from an economic point of view and suggest that the Riksbank did respond to house prices over the period 1993 to 2013.

Taken at face value, the results suggest that the Riksbank indeed reacted to house price inflation by setting a higher interest rate. The related studies of Iacoviello (2005) and Finocchiaro and Queijo von Heideken (2013) reveal similar evidence for the Federal Reserve, the Central Bank of Japan and the Bank of England. While monetary policy is likely to affect house prices by affecting the cost of borrowing, other factors are likely to be of importance as well. In the Swedish case, supply-side factors and the general borrowing conditions faced by households warrant special attention.

First, a large reduction of new housing supply in Sweden could have pushed house prices upward. For instance, in 2009 the number of completed apartments in one- or two-apartment dwelling house decreased by 28 per cent compared to the previous year.\(^\text{13}\)

Second, the role of (financial) regulations or deregulations in house price development should not be neglected. As emphasized by Hassler and Krusell (2010), the laxity of regulations can, among other things, result in a housing crisis. Svensson (2010) stresses that monetary policy is not enough to achieve macroeconomic stability, there are other instruments, like supervision and regulation, that should be considered as well. One factor that could have fostered the substantive increase in house prices during the sample period, is possibility of reckless residential mortgage lending in Sweden. However, the fairly recent decision of the Swedish Financial Supervisory Authority (Finansinspektionen) that households should not be allowed to borrow more than 85 percent of a property’s market

\(^{13}\)“Few solely-owned apartments in new production”. Press release from Statistics Sweden, 2010
value is likely to hamper excess borrowing.\textsuperscript{14} However, the stricter rules for amortization of new mortgages that are about to be implemented are also likely to deter households from excessive borrowing.

Finally, several possible extensions of this study are left for future work. First, the introduction of a financial sector would bring the model closer to reality and therefore fit the data better. Second, estimating a model with an optimal policy rule would deepen the understanding of the central bank’s optimal policy. Third, estimating a VAR model would allow for the comparison of parameter estimates using different methods.

\textsuperscript{14}Allmäna råd om begränsning av krediter mot säkerhet i form av pant i bostad, Finansinspektionen, Sverige, www.fi.se.
References


Finocchiaro, D. and V. Queijo von Heideken (2013), "Do Central Banks React to House Prices?", Journal of Money, Credit and Banking, 45, 1659 - 1683.


**Data bases**

Treasury Bills, Swedish market rates, Interest and Exchange rates, The Riksbank


The National Institute of Economic Research

www.konj.se

Real estate price index for one- and two-dwelling buildings for permanent living, Statistics Sweden

http://www.ssd.scb.se/databaser/makro/start.asp

National Accounts, Statistics Sweden

http://www.ssd.scb.se/databaser/makro/start.asp
Appendix 1

Figure 1: Deseasonalized series of real GDP, real consumption, real house prices, nominal interest rates and inflation.
Prior and posterior densities of the model parameters. Blue dotted lines correspond to prior densities, and black solid lines correspond to posterior densities.

Figure 2: Unrestricted model

Figure 3:Restricted model
Appendix 2

Notations and the full set of loglinearized equations is presented below.

Notations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>technology</td>
</tr>
<tr>
<td>I</td>
<td>real investment</td>
</tr>
<tr>
<td>K</td>
<td>capital</td>
</tr>
<tr>
<td>R</td>
<td>nominal interest rate</td>
</tr>
<tr>
<td>rr</td>
<td>real interest rate</td>
</tr>
<tr>
<td>X</td>
<td>markup of final over intermediate goods</td>
</tr>
<tr>
<td>Y</td>
<td>intermediate (final) output</td>
</tr>
<tr>
<td>b, b' b''</td>
<td>real borrowing, lending</td>
</tr>
<tr>
<td>c, c' c''</td>
<td>real consumption</td>
</tr>
<tr>
<td>h, h' h''</td>
<td>housing holdings</td>
</tr>
<tr>
<td>j</td>
<td>housing weight</td>
</tr>
<tr>
<td>m, m''</td>
<td>loan-to-value ratios</td>
</tr>
<tr>
<td>q</td>
<td>house prices</td>
</tr>
<tr>
<td>α</td>
<td>patient household wage share</td>
</tr>
<tr>
<td>β, β' β''</td>
<td>discount factor for households</td>
</tr>
<tr>
<td>γ</td>
<td>discount factor for entrepreneurs</td>
</tr>
<tr>
<td>δ</td>
<td>depreciation rate for K</td>
</tr>
<tr>
<td>η</td>
<td>labor disutility</td>
</tr>
<tr>
<td>θ</td>
<td>price rigidity</td>
</tr>
<tr>
<td>κ</td>
<td>Phillips curve slope</td>
</tr>
<tr>
<td>π</td>
<td>inflation</td>
</tr>
<tr>
<td>μ</td>
<td>capital share in production</td>
</tr>
<tr>
<td>ν</td>
<td>housing share in production</td>
</tr>
<tr>
<td>ψ</td>
<td>capital adjustment cost</td>
</tr>
<tr>
<td>rπ, rY, rq</td>
<td>coefficients on inflation, output and house price inflation in the Taylor rule</td>
</tr>
<tr>
<td>ρ</td>
<td>interest rate smoothing component in the Taylor rule</td>
</tr>
</tbody>
</table>

Aggregate demand

\[
\hat{Y}_t = \frac{c}{Y} \hat{c}_t + \frac{c'}{Y} \hat{c'}_t + \frac{c''}{Y} \hat{c''}_t + \frac{I}{Y} \hat{I}_t \tag{1}
\]

\[
\hat{c'}_t = \hat{c'}_{t+1} - \hat{r} \hat{r}_t + \hat{z}_t - \hat{z}_{t+1} \tag{2}
\]

\[
\hat{I}_t - \hat{K}_{t-1} = \gamma (\hat{I}_{t+1} - \hat{K}_{t+1}) + \frac{1 - \gamma(1 - \delta)}{\psi} (\hat{Y}_{t+1} - \hat{X}_{t+1} - \hat{K}_t) + \frac{\hat{c}_t - \hat{c}_{t+1}}{\psi} - \frac{\hat{z}_t - \hat{z}_{t+1}}{\psi} \tag{3}
\]

Housing/consumption margin
\[ \dot{q}_t = \gamma_e \dot{q}_{t+1} + \left(1 - \gamma_e\right)(\dot{Y}_{t+1} - \dot{X}_{t+1} - \dot{h}_t) - m\beta \ddot{r}_t - (1 - m\beta)(\dot{c}_{t+1} - \dot{c}_t - \dot{z}_{t+1} + \dot{z}_t) \] (4)

\[ \dot{q}_t = \gamma_h \dot{q}_{t+1} + (1 - \gamma_h)(\dot{j}_t + \dot{z}_t - \dot{h}_t) - m'' \beta \ddot{r}_t + (1 - m'' \beta)(\dot{c}''_t - \omega \dot{c}''_{t+1}) - (1 - m'' \beta)(\dot{z}_t - \omega \dot{z}_{t+1}) \] (5)

\[ \dot{q}_t = \beta \dot{q}_{t+1} + (1 - \beta) \dot{j}_t + \dot{h}_t + \nu \dot{h}''_t + \dot{c}''_t - \beta \dot{c}''_{t+1} - \beta \dot{z}_t + \beta \dot{z}_{t+1} \] (6)

**Borrowing constraints**

\[ \dot{b}_t = \dot{q}_{t+1} + \dot{h}_t - \ddot{r}_t \] (7)

\[ \dot{b}''_t = \dot{q}_{t+1} + \dot{h}''_t - \ddot{r}_t \] (8)

**Aggregate supply**

\[ \dot{Y}_t = \frac{\eta}{\eta - (1 - \nu - \mu)} (\dot{A}_t + \nu \dot{A}_{t-1} + \mu \dot{K}_{t-1}) - \frac{1 - \nu - \mu}{\eta - (1 - \nu - \mu)} (\dot{X}_t + \alpha \dot{c}'_t + (1 - \alpha) \dot{c}''_t) \] (9)

\[ \dot{\pi}_t = \frac{1}{1 + \beta} \dot{\pi}_{t-1} + \frac{\beta}{1 + \beta} \dot{\pi}_{t+1} - \kappa \dot{X}_t + \dot{u}_t \] (10)

**Flows of funds/evolution of state variables**

\[ \dot{K}_t = \delta \dot{K}_{t-1} + (1 - \delta) \dot{K}_{t-1} \] (11)

\[ \frac{b}{Y} \dot{b}_t = \frac{c}{Y} \dot{c}_t + \frac{q h}{Y} \Delta \dot{h}_t + \frac{I}{Y} \dot{I}_t + \frac{R h}{Y} (\dot{R}_{t-1} + \dot{b}_{t-1} - \dot{\pi}_t) - (1 - s' - s'')(\dot{Y}_t - \dot{X}_t) \] (12)

\[ \frac{b''}{Y} \dot{b}''_t = \frac{c''}{Y} \dot{c}''_t + \frac{q h''}{Y} \Delta \dot{h}''_t + \frac{R b''}{Y} (\dot{R}_{t-1} + \dot{b}''_{t-1} - \dot{\pi}_t) - s''(\dot{Y}_t - \dot{X}_t) \] (13)

**Monetary policy rule**

\[ \dot{R}_t = \rho \dot{R}_{t-1} + (1 - \rho) [r_\pi \dot{\pi}_t + r_\gamma \dot{Y}_t + r_\delta \Delta \dot{q}] + \dot{e}_{R,t} \] (14)

**Shock processes**

\[ \dot{j}_t = \rho_j \dot{j}_{t-1} + \dot{e}_{j,t} \] (15)

\[ \dot{A}_t = \rho_A \dot{A}_{t-1} + \dot{e}_{A,t} \] (16)

\[ \dot{z}_t = \rho_z \dot{z}_{t-1} + \dot{e}_{z,t} \] (17)

where \( \gamma_e = (1 - m) \gamma + m \beta \).
\[ \gamma_h = \beta'' + m''(\beta - \beta''), \]
\[ s' = (\alpha(1 - \mu - \nu) + X - 1)/X, \]
\[ s'' = (1 - \alpha)(1 - \mu - \nu)/X, \]
\[ \omega = (\beta'' - m'' \beta'')/(1 - m'' \beta), \]
\[ \iota = (1 - \beta) h/h', \]
\[ \iota'' = (1 - \beta) h''/h', \]
\[ \hat{\pi}t = \hat{R}_t - \hat{E}_t \hat{\pi}_{t+1}, \]
\[ \kappa = (1 - \theta)(1 - \beta \theta)/\theta. \]