Monetary Policy in an Estimated DSGE Model with a Financial Accelerator*

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Abstract

This paper estimates a sticky-price DSGE model with a financial accelerator to assess the importance of financial frictions in the amplification and propagation of the effects of transitory shocks. Structural parameters of two models, one with and one without a financial accelerator, are estimated using a maximum-likelihood procedure and post-war US data. The estimation and simulation results provide some quantitative evidence in favour of the financial accelerator model. The financial accelerator appears to play an important role in investment fluctuations, but its importance for output depends on the nature of the initial shock.

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1 Introduction

An extensive literature has argued that credit market frictions can amplify and propagate the effects of aggregate shocks to the macroeconomy (for example Bernanke and Gertler 1989, 1995 and Carlstrom and Fuerst 1997). Shocks have a larger or more persistent affect on macro variables because they affect firm balance sheets, changing the cost of borrowing over and above the traditional effects on interest rates. Bernanke, Gertler and Gilchrist(1999) (BGG hereafter) introduce such a credit market friction into a calibrated dynamic stochastic general equilibrium (DSGE) model with sticky prices. They argue that this friction leads to a "financial accelerator" mechanism that improves the ability of an otherwise standard model to explain normal cyclical fluctuations.

If credit frictions are quantitatively important for cyclical fluctuations, models used for monetary policy analysis should take them more seriously. The focus of this paper is to evaluate the importance of credit market frictions in amplifying and propagating the effects of transitory shocks on macroeconomic variables. To this end, we develop and estimate a sticky-price DSGE model that includes a financial accelerator mechanism similar to that of BGG. The structural parameters of the model, including those related to the financial accelerator are estimated econometrically using post-war U.S. macroeconomic data and a maximum-likelihood procedure with a Kalman filter. To evaluate the importance of the accelerator we compare the impulse responses of macro variables with and without the financial accelerator present. We also reestimate a constrained version of the model in which the financial accelerator is turned-off. Estimating these two versions of the model allows us to econometrically test for the presence of a finanical acclerator mechanism.

We find that the estimate of the parameter related to the financial accelerator is statistically significant and larger than in many calibrated studies. The impulse response functions show that introducing the financial accelerator helps to amplify and propagate the effects of all transitory shocks on investment. Its importance for the amplification of output fluctuations varies depending on the nature of the shock considered. The likelihood ratio test rejects the basic sticky price model without the financial accelerator in favour of the one that includes it.

1.1 Links to the literature

Bernanke and Gertler (1989) link the cost of a firms' external finance to the quality of their balance sheet.[1] Entrepreneurs, who borrow funds to undertake investment projects, face an external finance premium that rises as their personal stake in the project (net worth) falls. Declines in net worth lead to tighter financing conditions, reducing the demand for capital. This sets off an "accelerator" effect because the value of the capital held by firms (net worth) declines as the demand for capital falls resulting in a further rise in the cost of financing.

Carlstrom and Fuerst (1997) first demonstrated the quantitative importance of this mechanism. They inserted the same type of financial friction in an otherwise standard RBC model and found that it can reproduce the hump-shaped output response to shocks (propagation) that is seen in the data, but does not amplify the response of output. One drawback of their model is that it produces a procyclical external finance premium which is at odds with the data. Using a sticky-price model calibrated to post-war U.S. data, BGG show that a different set up for the financial accelerator mechanism both amplifies the impact of shocks and provides a quanti-

[1] An alternative approach is to introduce financial frictions by giving financial intermediaries an ability to change credit conditions without a change in borrower creditworthiness. Examples of these studies are Cook (1999), Cooper and Ejarque (2000), Atta-Mensah and Dib (2003), and Meh and Moran (2004).

tatively important mechanism that propagates shocks at business cycle frequencies. In addition, it generates a countercyclical risk premium.[2]

The literature on estimated DSGE models with financial frictions is emerging. Perhaps the closest to our study is Meier and Muller (2004) who consider the role of the BGG-style financial accelerator in the monetary transmission mechanism. They estimate their model by matching model impulse responses with the empirical impulse responses to a monetary policy shock from a VAR. Their findings attribute an important role to capital adjustment costs, but only a minor role to the accelerator in explaining the transmission of monetary policy shocks. We are interested not just in the transmission mechanism of monetary policy, but also the role of the accelerator in the amplification and propagation of other shocks. Neri(2004) estimates a DSGE model with a Carlstrom and Fuerst-style financial friction using Bayesian techniques. He finds that a model with both capital adjustment costs and this financial friction does better at explaining the data than either of these alone. Our objectives are similar, but we use the BGG accelerator set up, in part because we think the countercyclical risk premium is an attractive feature of that model. Christiano, Motto and Rostagno (2004) estimate a financial accelerator model of the U.S. during the Great Depression, but do not isolate its contribution to their findings. Like the first two studies, we consider only the post-war period in U.S. history and therefore consider normal cyclical fluctuations rather than financial crises.

The model developed here is based on Dib (2002) and Ireland (2001,2003). It

[2]Subsequent work using the BGG model for other countries has found similar results (see Hall (2001) for the UK and Fukunaga (2002) for Japan). A number of studies have used this financial accelerator mechanism to account for macroeconomic developments at times of financial crisis. Cespedes, Chang and Velasco (2004), Gertler, Gilchrist and Natalucci (2003), Tovar (2003, 2004), and Elekdag, Justiniano, and Tchakarov (2005) consider the case of open economies in emerging markets. Christiano, Motto and Rostagno (2004) use the financial accelerator in their analysis of the Great Depression in the U.S.

has the basic sticky price set up as in BGG, allowing for comparison with both BGG and with Ireland (2003). One important feature of the Ireland model is its emphasis on the estimation of the parameter associated with capital adjustment costs. This in important because the interaction of capital adjustment costs and sticky prices is key in allowing sticky price models to match important features of the data. In addition, in our context capital adjustment costs are pivotal in generating the asset price fluctuations that affect firm balance sheets, a key mechanism of the financial accelerator.

These models also have the advantage that they use a general class of monetary policy rule. This is useful because the behaviour of the monetary authorities has an impact on the quantitative importance of the financial accelerator. For example, BGG have noted that policy rules that stabilize output will also counteract, and may eliminate, the impact of the financial accelerator on output or investment (see Fukunaga (2002) for an example).[3] Also, to best capture the behaviour of the monetary authories in post-war data we need to use a rule that is general enough to allow for what is widely believed to be a fundamental change in Federal Reserve policy that appeared in mid-1979, ex. Clarida, Galí, and Gertler (2000). For now we present results based on the model estimated using data since 1979. [4]

This paper is organized as follows. Section 2 describes the model. Section 3 describes the data and the econometric method used to estimate the models. Section 4 discusses the empirical results and Section 5 concludes.

[3]Its effects may, nonetheless, show up elsewhere such as the size of the monetary policy response required to dampen output fluctuations.

[4]However, we plan to estimate the model for the 1959Q1 to 1979Q2 period separately as in Ireland (2003), which would allow the monetary policy parameters to change.

2 The Model

Our basic model is a closed economy DSGE model similar to Dib (2002) and Ireland(2001,2003). The key addition to this model is a financial accelerator mechanism similar to that proposed by BGG. As a result, we assume that the economy is characterized by three types of rigidities: price stickyness, capital adjustment costs, and financial market frictions. We also assume the economy is disturbed by five transitory shocks: technology, money demand, monetary policy, preference, and investment efficiency shocks.

In this model there are three types of producers: entrepreneurs; capital producers; and retailers. Entrepreneurs produce intermediate goods. They borrow from a financial intermediary that converts household deposits into business financing for the purchase of capital. The presence of asymmetric information between entrepreneurs and lenders creates a financial friction which makes entrepreneurial demand for capital depend on their financial position. Capital producers build new capital and sell it to entrepreneurs. Changes in the supply of or demand for capital will lead the price of capital to fluctuate and further propagate the shocks. Retailers set nominal prices in a staggered fashion à la Calvo (1983). This nominal rigidity gives monetary policy a role in this model. Our model differs from BGG in its characterization of monetary policy by a modified Taylor-type rule. We assume that the Federal Reserve manages short-term interest rates in response to inflation, output, and money growth changes. In addition, we allow for the possibility of debt deflation and a utility function that is non-separable in consumption and real balances.

2.1 Households

The representative household derives utility from consumption, c_t; real money balances, M_t/p_t; and leisure, $1 - h_t$. Its preferences are described by the following expected utility function:

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t u\left(c_t, M_t/p_t, h_t\right), \tag{1}$$

where $\beta \in (0,1)$ is the discount factor, M_t is holdings of nominal money balances, h_t is labour supply, and p_t is the consumer price level. The single-period utility function is specified as:

$$u(\cdot) = \frac{\gamma z_t}{\gamma - 1} \log\left[c_t^{\frac{\gamma-1}{\gamma}} + b_t^{1/\gamma}\left(\frac{M_t}{p_t}\right)^{\frac{\gamma-1}{\gamma}}\right] + \eta \log\left(1 - h_t\right), \tag{2}$$

where $\gamma > 0$ and $\eta > 0$ denote the constant elasticity of substitution between consumption and real balances, and the weight on leisure in the utility function, respectively. We interpret z_t as a taste (preference) shock, while b_t is interpreted as a money demand shock. These shocks follow first-order autoregressive processes:

$$\log(z_t) = \rho_z \log(z_{t-1}) + \varepsilon_{zt}, \tag{3}$$

and

$$\log(b_t) = (1 - \rho_b)\log(b) + \rho_b \log(b_{t-1}) + \varepsilon_{bt}, \tag{4}$$

where $\rho_z, \rho_b \in (-1,1)$ are autoregressive coefficients, b is constant, and the serially uncorrelated shocks ε_{zt} and ε_{bt} are normally distributed with zero means and standard deviations σ_z and σ_b, respectively.

The representative household enters period t with d_{t-1} units of real deposits in the financial intermediary; nominal money balances, M_{t-1}; and nominal bonds, B_{t-1}.

While deposits, d_t, at the financial intermediary pay interest, money balances, M_t, are money held outside of banks (cash) or low interest bearing savings instruments such as chequing accounts.[5] The inclusion of money balances is motivated, in part, by empirical evidence that money demand shocks matter for business cycles. During period t the household chooses to consume, c_t; purchase new government bonds, B_t; change money balances $\frac{M_t}{p_t}$; deposit funds at the financial intermediary, d_t; and work h_t. The budget constraint is

$$c_t + \frac{d_t}{R_t} + \frac{M_t + B_t/R_t^n}{p_t} \leq \frac{W_t}{p_t} h_t + d_{t-1} + \frac{M_{t-1} + B_{t-1} + T_t + D_t}{p_t}, \tag{5}$$

First-order conditions for the household optimization problem are:

$$\frac{z_t c_t^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + b_t^{1/\gamma} m_t^{\frac{\gamma-1}{\gamma}}} = \lambda_t; \tag{6}$$

$$\frac{z_t b_t^{1/\gamma} m_t^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + b_t^{1/\gamma} m_t^{\frac{\gamma-1}{\gamma}}} = \lambda_t - \beta E_t \left(\frac{\lambda_{t+1}}{\pi_{t+1}} \right); \tag{7}$$

$$\frac{\eta}{1 - h_t} = \lambda_t w_t; \tag{8}$$

$$\frac{1}{R_t} = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \right]; \tag{9}$$

$$\frac{1}{R_t^n} = \beta E_t \left[\frac{\lambda_{t+1}}{\pi_{t+1} \lambda_t} \right], \tag{10}$$

where λ_t is the Lagrangian multiplier associated with the budget constraint; $m_t = M_t/p_t$, $w_t = W_t/p_t$, $\pi_{t+1} = p_{t+1}/p_t$.

[5] The real return on bonds and deposits is the same in equilibrium. We introduce nominal (bonds) and real (deposits) assets to explicity derive the Fisher equation.

2.2 Production sector

2.2.1 Entrepreneurs

The entrepreneurs' behaviour folloes that proposed by Bernanke, Gertler and Gilchrist (1999). Entrepreneurs manage firms that produce wholesale goods and borrow to finance the capital used in the production process. Entrepreneurs are risk neutral and have a finite expected horizon for planning purposes. The probability that an entrepreneur will survive until the next period is ν, so the expected lifetime horizon is $1/(1-\nu)$. This assumption ensures that entrepreneurs' net worth (the firm equity) will never be enough to fully finance the new capital acquisition. In essence, they issue debt contracts to finance their desired investment expenditures in excess of net worth.

At the end of each period, entrepreneurs purchase capital that will be used in the next period, $q_t k_{t+1}$. The capital acquisition is financed partly by their net worth n_{t+1} and by borrowing $q_t k_{t+1} - n_{t+1}$ from a financial intermediary. This intermediary obtains its funds from household deposits and faces an opportunity cost of funds equal to the economy's riskless rate of return, R_t^n.

The entrepreneurs' demand for capital depends on the expected marginal return and the expected marginal external financing cost. Consequently,

$$E_t f_{t+1} = E_t \left[\frac{r_{kt+1} + (1-\delta) q_{t+1}}{q_t} \right], \tag{11}$$

where f_{t+1} is the interest rate on external (borrowed) funds and and r_{kt+1} is the marginal productivity of capital at $t+1$. Following BGG (1999), we assume the existence of an agency problem that makes external finance more expensive than internal funds. The entrepreneurs costlessly observe their output which is subject to a random outcome. The financial intermediaries incur an auditing cost to observe an entrepreneur's output. After observing his project outcome, an entrepreneur decides whether to repay his debt or to default. If he defaults the financial intermediary audits the loan and recovers the project outcome less monitoring costs.

Accordingly, the marginal external financing cost is equal to a gross premium for external funds plus the gross real opportunity costs equivalent to the riskless interest rate. Thus, the demand for capital should satisfy the following optimality condition:

$$E_t f_{t+1} = E_t \left[S(\cdot) R_t \right], \tag{12}$$

where $E_t R_t = E_t \left(R_t^n / \pi_{t+1} \right)$ is a riskless real interest rate and

$$S(\cdot) = E_t S \left(\frac{n_{t+1}}{q_t k_{t+1}} \right), \tag{13}$$

with $S'(\cdot) < 0$ and $S(1) = 1$.

The gross external finance premium $S(\cdot)$ depends on the size of the borrower's equity stake in project (or alternatively the borrower's leverage ratio). As $n_{t+1}/q_t k_{t+1}$ falls, the borrower relies on uncollateralized borrowing (higher leverage) to a larger extent to fund his project. Since this increases the incentive to misreport the outcome of the project the loan becomes riskier and the cost of borrowing rises.[6]

Aggregate entrepreneurial net worth evolves according to

$$n_{t+1} = \nu v_t + (1 - \nu) g_t, \tag{14}$$

where v_t denotes the net worth of surviving entrepreneurs net of borrowing costs carried over from the previous period. $1 - \nu$ is the share of new entrepreneurs entering the economy and g_t is the transfer or "seed money" that newly entering

[6]Note that when the riskiness of loans increases the agency costs rise and the lender's expected loses increase. A higher external finance premium paid by successful entrepreneurs offsets these higher loses and ensures that there is no change to the return on deposits for households.

entrepreneurs receive from entrepreneurs that die and depart from the scene. v_t is given by

$$v_t = [f_t q_{t-1} k_t - E_{t-1} f_t (q_{t-1} k_t - n_t)] \tag{15}$$

where f_t is the ex post real return on capital held in t, and $E_{t-1} f_t$ is the ex post cost of borrowing. Earnings from operations this period become next period's net worth.

To produce output y_t, the entrepreneurs use k_t units of capital and h_t units of labour following constant-returns-to-scale technology:

$$y_t \leq k_t^{\alpha} \left(A_t h_t\right)^{1-\alpha}, \quad \alpha \in (0, 1), \tag{16}$$

where A_t is a technology shock that is common to all entrepreneurs. The technology shock A_t is assumed to follow the autoregressive process

$$\log A_t = (1 - \rho_A) \log(A) + \rho_A \log(A_{t-1}) + \varepsilon_{At}, \tag{17}$$

where ρ_a (-1,1), $A > 0$, and ϵ_{At} is normally distributed with zero mean and standard deviation σ_A.

The first-order conditions for this optimization problem are

$$r_{kt} = \alpha \frac{y_t}{k_t} \frac{\xi_t}{\lambda_t}; \tag{18}$$

$$w_t = (1 - \alpha) \frac{y_t}{h_t} \frac{\xi_t}{\lambda_t}; \tag{19}$$

$$y_t = k_t^{\alpha} \left(A_t h_t\right)^{1-\alpha}. \tag{20}$$

where $\xi_t > 0$ is the Lagrangian multiplier associated with the technology function, and ξ_t / λ_t is the real marginal cost, MC_t / p_t.[7]

[7] We assume that entrepreneurial consumption is small and it drops out of the model.

2.2.2 Capital producers

Capital producers use a linear technology to produce capital goods, k_t, sold at the end of period t. They also use a fraction of final goods purchased from retailers. The produced capital goods replace depreciated capital and add to the capital stock. We assume that capital producers are subject to quadratic capital adjustment costs. Their optimization problem, in real terms, is:

$$\max_{i_t} = E_t \left[q_t i_t - i_t - \frac{\chi}{2} \left(\frac{i_t}{k_t} - \delta \right)^2 k_t \right]. \tag{21}$$

Thus, the optimal condition is

$$E_t \left[q_t - 1 - \chi \left(\frac{i_t}{k_t} - \delta \right) \right] = 0; \tag{22}$$

which is the standard Tobin's Q equation that relates the price of capital to the marginal adjustment costs.

The quantity and price of capital are determined in the market for capital. The entrepreneurial demand curve for capital is determined by equations (11) and (18) and the supply of capital is given by equation (22). The intersection of these curves gives the quantity and price of capital. Capital adjustment costs slow down the response of investment to different shocks, which directly affects the price of capital.

Furthermore, the aggregate capital stock evolves according to

$$k_{t+1} = x_t i_t + (1 - \delta) k_t. \tag{23}$$

where δ is the depreciation rate and the disturbance x_t is a shock to the marginal efficiency of investment (as in Greenwood et al. (1998)). The x_t shock follows the autoregressive process:

$$\log(x_t) = \rho_x \log(x_{t-1}) + \varepsilon_{xt}, \tag{24}$$

where ρ is normally distributed with standard deviation σ_x.

2.2.3 Retailers

The retailers purchase the wholesale goods at a price equal to nominal marginal costs MC_t and differentiate them at no cost.[8] They then sell these differentiated retail goods on a monopolistically competitive market. Following Calvo (1983), we assume that retailers cannot change their selling prices unless they receive a random signal. The constant probability of receiving such a signal is $(1-\phi)$. Thus, each retailer j sets the price $\bar{p}_t(j)$ that maximizes the expected profit for l periods. [9] The retailer's optimization problem is

$$\max_{\{\bar{p}_t(j)\}} E_0 \left[\sum_{t=0}^{\infty} (\beta\phi)^l \lambda_{t+l} D_{t+l}(j)/p_{t+l} \right], \tag{25}$$

subject to[10]

$$y_{t+l}(j) = \left(\frac{\bar{p}_t(j)}{p_{t+l}} \right)^{-\theta} y_{t+l}, \tag{26}$$

where the retailer's profit function is

$$D_{t+l}(j) = \left(\bar{p}_t(j) - MC_{t+l}\right) y_{t+l}(j). \tag{27}$$

[8]The retail sector is used only to introduce nominal rigidity into this economy.

[9]l is the average length of time a price remains unchanged, $l = 1/(1-\phi)$.

[10]This demand function is derived from the definition of aggregate demand as the composite of individual final output (retail) goods and the corresponding price index in the monopolistic competition framework of Dixit and Stiglitz (1997) as follows

$$y_{t+l} = \left(\int_0^1 y_{t+l}(j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}$$

$$p_{t+l} = \left(\int_0^1 p_{t+l}(j)^{1-\theta} dj \right)^{\frac{1}{1-\theta}}$$

where $y_{t+l}(j)$ and $p_{t+l}(j)$ are the demand and price faced by each individual retailer $j \in (0,1)$

The first-order condition is:

$$\bar{p}_t(j) = \frac{\theta}{\theta - 1} \frac{E_t \sum_{l=0}^{\infty} (\beta\phi)^l \lambda_{t+l} MC_{t+l} y_{t+l}(j)/p_{t+l}}{E_t \sum_{l=0}^{\infty} (\beta\phi)^l \lambda_{t+l} y_{t+l}(j)/p_{t+l}}. \tag{28}$$

The aggregate price is

$$p_t^{1-\theta} = \phi p_{t-1}^{1-\theta} + (1-\phi)\bar{p}_t^{1-\theta}. \tag{29}$$

These equations lead to the following New Keynesian Phillips curve

$$E_t \hat{\pi}_{t+1} = \hat{\pi}_t - \frac{(1-\beta\phi)(1-\phi)}{\phi} \hat{mc}_t \tag{30}$$

where mc_t is real marginal cost and variables with hats are log deviations from the steady state value ($\hat{x}_t = \log(x_t/x)$).

2.3 Monetary authority

Following Ireland (2004), the central bank adjusts the nominal interest rate, R_t^n, in response to deviations of inflation, $\pi_t = p_t/p_{t-1}$, output, y_t, and money growth rate $\mu_t = M_t/M_{t-1}$ from their steady-state values. Thus, the monetary policy rule evolves according to:

$$\log(R_t^n/R^n) = \varrho_\pi \log(\pi_t/\pi) + \varrho_y \log(y_t/y) + \varrho_\mu \log(\mu_t/\mu) + \varepsilon_{Rt} \tag{31}$$

where R^n, π, y, and μ are the steady-state values of R_t^n, π_t, y_t, and μ_t, respectively; ε_{Rt} is a monetary policy shock normally distributed with zero mean and standard deviation σ_R. The newly created money is transfered to households, so $T_t = M_t - M_{t-1}$. By reacting to money growth deviations, the central bank tries to insulate the economy from the effects of money demand shocks.

We choose this policy rule to provide more flexibility in the characterization of monetary policy than the rule in BGG, which contains only the interest rate smoothing term and the lagged deviation of inflation from its steady state.[11] Allowing for a stronger output stabilizing response of monetary policy may have an impact on the conclusions regarding the importance of the financial accelerator. Also, we plan to estimate the model over the 1959-1979 period, so this flexibility will help to better characterize any change in Federal Reserve behaviour. For example, if ϱ_μ is non-zero, monetary policy can be considered to influence a linear combination of the interest rate and money growth to achieve a target for inflation.

2.4 Symmetric equilibrium

In the symmetric equilibrium, all entrepreneurs are identical, so they make the same decision. In this economy, the symmetric equilibrium consists of an allocation $\{y_t, c_t, m_t, i_t, h_t, k_t, n_t\}$ and a sequence of prices and co-state variables $\{w_t, r_{kt}, R_t^n, R_t, f_t, q_t, \lambda_t, mc_t\}$ that satisfy the optimality conditions of households, capital producers, entrepreneurs, and retailers; the money-supply rule; and the stochastic processes for preferences, money demand, productivity, investment and monetary policy shocks (see Appendix A).

Taking a log-linear approximation of the equilibrium system around steady-state values and using Blanchard and Kahn's (1980) procedure yields a state-space solution of the form:

$$\hat{\mathbf{s}}_{t+1} = \Phi_1 \hat{\mathbf{s}}_t + \Phi_2 \varepsilon_{t+1}, \tag{32}$$

$$\hat{\mathbf{d}}_t = \Phi_3 \hat{\mathbf{s}}_t. \tag{33}$$

The state variable vector, $\hat{\mathbf{s}}_t$, includes predetermined and exogenous variables; $\hat{\mathbf{d}}_t$ is

[11] In addition, they set the weight on inflation deviations equal to 0.11.

the vector of control variables; and the vector ε_t contains the random innovations. The coefficient matrices, Φ_1, Φ_2, and Φ_3, have elements that depend on the structural parameters of the model. Therefore, the state-space solution, (34)–(35), is used to estimate and simulate the model.

3 Calibration and Data

As in previous studies that estimate DSGE models using a maximum-likelihood procedure, some parameters have to be set prior to estimation because the data used contain little information about them. Thus, the parameter η, denoting the weight on leisure in the utility function, is set equal to 1.315, so that the household spends around 33 per cent of its time in market activities. The degree of retailers' monopoly power, θ, is set equal to 6, which implies a gross steady-state price markup of 1.20. The depreciation rate, δ, is assigned the commonly used values of 0.025. The constant associated with money demand,b, is set to 0.07.[12]

We also calibrate some of the parameters related to the credit market friction. We fix the steady state interest rate on external funds equal to the average of the business prime loan rate over our sample (this gives a gross external finance premium, $S(\cdot)$, of about 1.03 or 3.0 per cent per year on a net basis). We set the steady state debt-to-asset (leverage) ratio equal to 2 and the probability that an entrepreneur will survive for the next period, ν, to 0.9728, as in BGG (1999).[13]

The remaining non-calibrated parameters are estimated using a maximum-likelihood procedure with a Kalman filter. This method applies a Kalman filter to a model's state-space form to generate series of innovations used to evaluate the likelihood

[12]This parameter was difficult to estimate.

[13]Therefore, on the average, an entrepreneur may live 36 years.

function for the sample. Because the solution is a state-space econometric model, driven by five innovations in ε_t, the structural parameters embedded in Φ_1, Φ_2, and Φ_3 can be estimated by a maximum-likelihood procedure using data for five series, in this case y_t, i_t,π_t, R_t and m_t.[14]

Using quarterly US data from 1979Q3 through 2004Q3, we estimate two versions of the model. The first is a model with a financial accelerator (hereafter referred to as the FA model). The second is the same model with the dynamic effects of the financial accelerator turned off. In this model the parameter that captures the elasticity of the external finance premium with respect to firm leverage ψ is constrained to equal zero.[15] We call this the Estimated No-FA Model.

Output is measured by real GDP excluding government expenditures, since there is no government spending in the model. Ireland(2003) argues that investment data is required because using only output data is insufficient to identify the capital adjustment cost parameter. Investment is real expenditures on machinery and equipment and non-residential construction. Real balances are measured by dividing the base money stock by the GDP deflator. These two series are expressed in per capita terms using the civilian population aged 16 and over. The inflation rate is measured by changes in the GDP implicit price deflator, while the short-term nominal interest rate is measured by the rate on three-month treasury bills. All the series are HP-filtered before the estimation.[16]

[14]This method is decribed in Hamilton (1994, Chap. 13)
[15]See the linearized equations in Appendix C.
[16]Inflation and interest rates exhibit a small downward trend over the post-1979 sample.

4 Empirical Results

4.1 Parameter estimates

Table 1 reports the maximum-likelihood estimates and standard errors of the FA and Estimated No-FA model's structural parameters for the 1979Q3 to 2004Q3 period. The estimates of γ, the constant elasticity of substitution between consumption and real balances, is 0.026 and the estimate of the capital share in the production function, α, is close to 0.33.

The capital adjustment cost parameter, χ, is 1.43 in the FA model more than double the 0.64 estimated in the the Estimated No-FA model. These estimates are considerably higher than the 0.25 value for the adjustment cost parameter used by BGG. However, using a similar econometric methodology, Ireland (2001,2003) finds estimates of the adjustment cost parameter that are much larger.[17] The estimates of ϕ, the probability that prices remain unchanged for the next period, is about 0.5 in both models. This indicates that firms set prices for about 2 quarters on average.[18] Thus prices are quite flexible compared to other estimated DSGE models with Calvo pricing. The estimates of all the monetary policy rule parameters are statistically different from zero. The policy rule in the FA model responds more aggressively to inflation, output and money growth deviations. The estimate of ϱ_π, the coefficient that measures the response of monetary policy to inflation deviations is 1.94 in the FA model, but much less, 0.91, in the No-FA model. The estimates of ϱ_y are small, but statistically significant and take the expected sign in both models. The estimated value of ϱ_μ, the weight on money growth deviations, is 0.41 in the

[17]The estimated value for χ in Ireland (2003) 32.1 in the post-1979 sample.

[18]Prices are somewhat stickier in BGG with $\phi = 0.75$ implying and average period between price adjustments of 4 quarters.

FA model, but a much smaller 0.15 in the No-FA model.In both models, estimates of the policy rule parameters indicate that since 1979 the Fed has responded much more strongly to inflation deviations than to output or money growth fluctuations.

The estimate of the parameter ψ, the elasticity of the external finance premium with respect to firm leverage, is statistically significant and equal to 0.092. This estimate is higher than values usually used to calibrate this parameter in models with a financial accelerator. For example, Bernanke and Gertler (2000) set ψ to 0.05 about half of our estimated value. This value is sometimes calibrated with an eye to matching historical averages over much of the post-war period of the spread between the prime business loan rate and the risk-free rate and the ratio of business debt to assets. The difference in values of ψ may be due to using data that span much more of the post-war period than we use for estimation.

Do the dynamic effects associated with fluctuations in net worth and the risk premium allow the FA model to better capture the comovement in the data? We use the likelihood-ratio test to test the restriction imposed by the No-FA model ($\psi = 0$) against the model with the financial accelerator (FA model). Let L^u and L^c denote the maximum values of the log-likelihood function for the unconstrained (FA) and constrained (No-FA) models, respectively. The likelihood ratio statistic $-2(L^c - L^u)$ has a chi-square distribution with two degrees of freedom under the null hypothesis that the No-FA is valid. The value of L^u is 1896.8 and L^c is 1871.4 giving a test statistic of 50.8. The 2 per cent critical value for a $\chi^2(2)$ is 9.21. Therefore, the likelihood ratio test easily rejects the restrictions of the No-FA model in favour of the model that includes a financial accelerator.[19]

[19]Note that this is not an empirical test for the existence of a financial frictions since one must exist in both models because the steady state cost of external funds exceeds the risk-free rate. This is a test of the extent to which such a friction improves the models ability to account for the dynamics of macrovariables seen in the data

4.2 Impulse responses

Next we compare the responses of various macroeconomic variables to five different shocks when the financial accelerator is present and when it is not. Figures 1 to 5 display the impulse responses to a 1 per cent shock to the short-term nominal interest rate (tightening of monetary policy), technology (increase in A_t), money demand (increase in b_t), preferences for consumption (increase in z_t) and the efficiency of investment (increase in x_t). Each variable's response is expressed as the percentage deviation from its steady-state level, except rates which are in percentage points (e.g. a 0.1 increase in $\hat{R}_t^n$ is an increase of 10 basis points).

In figures 1 to 5 the impulse responses generated in the estimated FA model are shown in red. The dashed lines (in blue) are impulse responses when the dynamic effects of the financial accelerator are not present. They are the impulse responses generated by setting ψ equal to 0, but keeping all of the other parameter estimates from the FA model (we call this the No-FA model). The difference between the red and blue lines should indicate the impact of the accelerator mechanism on a given variable after a particular shock. Since the likelihood-ratio test rejects the estimated model in which ψ is constrained to equal zero, its impulse responses are not shown here.

Figure 1 shows that the presence of a financial accelerator both amplifies and propagates the impact of a positive 1 per cent monetary policy shock on real variables, particularly for investment. Despite the fact that the shock only lasts for one period, deviations of investment, output and hours are long-lived. The basic mechanism of the financial accelerator is evident in the impulse responses. After a tightening in monetary policy, net worth falls because of the declining return to capital and the higher real interest costs associated with existing debt (debt-deflation effect). The external finance premium rises reflecting the increase in firm leverage. The higher funding cost of purchasing new capital depresses the demand for new capital and the expected price of capital persists below its steady state value.

Figure 2 shows that following a 1 per cent positive technology shock there is an important amplification of investment but no amplification of the output response when the financial accelerator is present. Again the impact on output, investment and hours lingers in the FA model responses. Here the technology shock increases the return to capital pushing up net worth. The small decline in inflation that results from the shock increases the real cost of repaying existing debt, dampening the rise of net worth slightly. The positive impact on net worth from the higher return to capital dominates, in part due to the endogenous policy response that reduces the disinflationary impact, and net worth rises. Higher net worth decreases the external finance premium and increases the demand for capital. Again the response of investment to the shock is much larger when the FA is present. As is often found in sticky-price models, hours worked declines after the technology shock as the wealth effect from higher marginal product of labour outweighs the substitution effect. However, the decline in hours worked is not very different in the FA and No-FA cases. The model estimated with no financial accelerator shows a more persistent response of output, but this is due to a higher estimated persistence coefficient of technology shock.

Figure 3 shows the impulse responses to a positive 1 per cent money-demand shock. As the demand for real balances rises, consumption and savings falls depressing output and investment. In addition, with less output being produced, but more liquidity in the economy expected inflation rises. The monetary authority responds with higher interest rates and an increased supply of money since the interest elasticity of money demand is small. In the FA model the initial drop in the return to capital has a larger impact on output and investment due to the accelerator effects.

Figure 4 shows the impulse responses to a positive 1 per cent shock to the marginal utility of consumption and real balances. The presence of a financial accelerator dampens the impact of the shock slightly from the the No-FA case. This is due to its influence on investment, which declines more sharply when the accelerator is present (consumption is almost identical in the two cases). The preference shock initially raises the marginal utility of consumption and therefore the opportunity cost of holding deposits (savings). As households divert deposits toward consumption the return on deposits (the risk free real interest rate) rises. In the accelerator model the rise in this interest rate has an larger effect on investment due to the impact on firms' net worth.

Figure 5 shows the impulse responses to an investment efficiency shock. This is a persistent positive shock to the marginal efficiency with which investment goods are turned into capital. Impulse responses from the FA model show that after such a shock investment drops sharply, but the capital stock increases. This is possible because the higher marginal efficiency of investment is a perfect substitute for investment and more than compensates for its decline. Investment falls because future marginal product of capital declines and capital adjustment costs increase as the capital stock rises. In the FA model the decline in investment is more pronounced. The rise in the supply of capital reduces its price and lowers the return on capital and hence net worth. The resulting rise in the external finance premium makes the cost of funding investment purchases even higher. The fact that a positive productivity shock to investment causes an increase in the risk premium may be particular to the form of capital adjustment costs in the model. We plan to consider and alternative form of adjustment cost in the future.

As in previous studies, the FA amplifies and propagates the impact of the shocks on investment. The importance of the FA for output fluctuations, however, depends on the shock. For the monetary policy, money demand and investment efficiency shocks the initial impact on output is double (or more) when the FA is present. However, the FA has no impact on the initial response of output after a technology shock though the effects are more persistent. In the case of the shock to the marginal utility of consumption output actually responds less when the FA is present.

4.3 Volatility and autocorrelation

Table 3 reports the volatilities of output, investment, money growth (μ_t), interest rates and inflation from the data and for simulated versions of the FA model with the accelerator active and with it turned off.[20] The standard deviations are expressed in percentage terms. In the data, investment is about 5 times as volative as output, the standard deviation of output is 1.04 and investment is 5.6. Money growth has a standard deviation of 0.85 percent . The short-term nominal interest rate and inflation are less volatile; their standard deviations are 0.31 per cent and 0.21 per cent, respectively.

The simulation results show that output volatility in the FA model when the accelerator is active is close to the volatility of output in the data. However, the model in which the accelerator is inactive overpredicts output volatility to a large degree. This is a feature common to sticky-price models. It is interesting that the FA model which contains an extra friction meant to amplify and propagate

[20]In the data, all series are HP-filtered before calculating their standard deviations.

shocks shows less output volatility. All of the models overpredict the volatility of investment, but not the ratio of investment volatility to output volatility. In the FA model, investment is almost 9 times as volatile as output compared with about 5 times in the data. In the model with the FA inactive, investment is not even twice as volatile as output. Both versions of the model do well at replicating the volatility of money growth and overpredict the volatility of nominal interest rates. Both models also generates inflation volatility higher than that seen in the data.

Figure 6 plots the autocorrelation functions for output, investment, money, nominal interest rates and inflation generated by our models and in the data. The model with the active FA mechanism model does a better job at matching the autocorrelations seen in the data. It does a good job of matching the autocorrelation in inflation and nominal interest rate within a 4 quarter horizon. However, output and investment in the FA model are still much more highly autocorrelated than are the data.

4.4 Variance decompositions

Tables 4 and 5 decompose the forecast-error variance of detrended output and inflation owing to technology, money demand, monetary policy, preference and investment efficiency shocks. Again, results are shown for the FA model with the accelerator is active and when it it turned off. Table 2 decomposes the forecast-error variance of detrended output. As shown in Panel A, the FA model implies that technology, preference and investment shocks explain almost all of the output fluctuations in both the near and the long term. Surprisingly, monetary policy shocks play a role in output fluctuations in the long run. In contrast, Panel B shows that, in the model with the FA shut off, preference shocks and aggregate technology shocks are most important for output fluctuations at short horizons, accounting for 52 per cent and 40 per cent (respectively) of the variance in output at the one-quarter-ahead horizon. Investment shocks account for 95 per cent of output fluctuations at a 50 quarter horizon.

Table 5 decomposes the forecast-error variance of inflation. Panel A shows that all of the shocks play a role in short-run inflation fluctuations in the FA model. Money demand shocks are most important in the long-run, accounting for 32 per cent of inflation fluctuations. In the model with the FA shut off, technology and monetary policy shocks account for most of the short-term fluctuation in inflation. Monetary policy shocks account for about 43 per cent of the one-step-ahead inflation forecast-error variance. While these shocks are also important for long-run fluctuations in inflation, investment shocks play a relatively more important role.

5 Conclusion

There is a growing literature focusing on the importance of financial frictions in the amplification and propagation of transitory shocks in the context of DSGE models. In this paper, we introduce the financial accelerator à la Bernanke, Gertler, and Gilchrist (1999) into a standard sticky-price model to econometrically assess the role of the financial accelerator in post-war US business cycles.

Using quarterly data and a maximum-likelihood procedure with a Kalman filter, we estimate two versions of the model, one with and one without the financial accelerator. Estimated values of the elasticity of the external finance premium with respect to the leverage ratio are statistically significant and higher than often assumed in calibrated studies. A likelihood ratio test rejects the model without a financial accelerator in favour of the one with it. The impulse response functions show that introducing the financial accelerator helps to amplify and propagate the effects of all transitory shocks on investment. Its importance for the amplification of output fluctuations varies depending on the nature of the shock considered.

Future work wish to explore estimating the underlying parameters of the financial contract rather than taking the reduced form approach employed here. We could also extend this model to include further real frictions, more sources of persistence, and some exogenous financial shocks. This might allow the model to better match the empirical responses of macroeconomic variables to different shocks. We may also extend this work to analyze the role of the financial accelerator in a small open economy model.

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Table 1: Maximum-likelihood estimates: 1979Q3 to 2004Q3

	FA Model		No-FA Model	
Parameters	Estimates	Std. errors	Estimates	Std. errors
ψ	0.0922	0.0102	-	-
α	0.3412	0.0382	0.3234	0.0390
γ	0.0267	0.0048	0.0195	0.0034
χ	1.4264	0.5809	0.6428	0.3719
ϕ	0.4939	0.0091	0.4816	0.0731
ϱ_π	1.9440	0.2616	0.9141	0.0425
ϱ_y	0.0836	0.0256	0.0466	0.0188
ϱ_μ	0.4157	0.0502	0.1518	0.0320
σ_R	0.0050	0.0007	0.0033	0.0003
ρ_A	0.7599	0.0623	0.8502	0.0869
σ_A	0.0060	0.0008	0.0033	0.0007
ρ_b	0.6177	0.0531	0.8351	0.0623
σ_b	0.0101	0.0004	0.0085	0.0008
ρ_z	0.6684	0.0597	0.9565	0.0148
σ_z	0.0086	0.0008	0.0137	0.0017
ρ_x	0.8877	0.0364	0.9798	0.0251
σ_x	0.0841	0.0147	0.1207	0.0318
LL	1896.8		1871.4	

Table 3: Standard deviations: data and models

Variables	Data	FA Model	FA Model, $\psi = 0$
y	1.04	1.22	4.85
i	5.61	10.78	8.54
μ_t	0.85	0.87	0.91
R_t^n	0.31	0.42	0.43
π_t	0.21	0.28	0.39

Table 4: Forecast-error variance decomposition of detrended output

		Percentage owing to:				
Quarters	Variance	Technology	Money demand	Policy	Preference	Investment
			A. FA Model			
1	0.0036	26.38	4.43	6.70	26.34	36.14
2	0.0056	31.24	3.26	4.99	23.57	36.95
4	0.0075	35.19	2.53	4.27	20.16	37.85
10	0.0087	38.38	2.22	5.19	17.60	36.60
50	0.0121	34.32	1.73	12.33	14.21	37.41
			B. FA Model with FA shut off			
1	0.0023	40.55	2.29	3.89	52.54	0.73
2	0.0035	47.67	1.47	2.61	47.59	0.65
4	0.0049	50.20	1.07	1.88	40.12	6.73
10	0.0111	26.20	0.47	0.83	18.33	54.16
50	0.1083	2.74	0.05	0.09	1.89	95.23

Table 5: Forecast-error variance decomposition of inflation

		Percentage owing to:				
Quarters	Variance	Technology	Money demand	Policy	Preference	Investment
			A. FA Model			
1	0.0004	11.38	13.89	27.13	32.75	14.85
2	0.0006	8.22	27.40	21.07	30.57	12.74
4	0.0007	7.36	34.01	17.65	28.78	12.19
10	0.0007	7.15	33.94	16.59	27.81	14.51
50	0.0008	7.04	32.12	16.12	26.41	18.31
			B. FA Model with FA shut off			
1	0.0005	40.55	5.06	42.91	9.69	1.79
2	0.0005	39.54	6.91	40.74	11.13	1.68
4	0.0006	37.94	9.97	38.66	11.70	1.72
10	0.0006	36.28	10.23	36.85	11.42	5.22
50	0.0010	21.95	6.18	22.28	6.91	42.67

Figure 1: Monetary policy shock

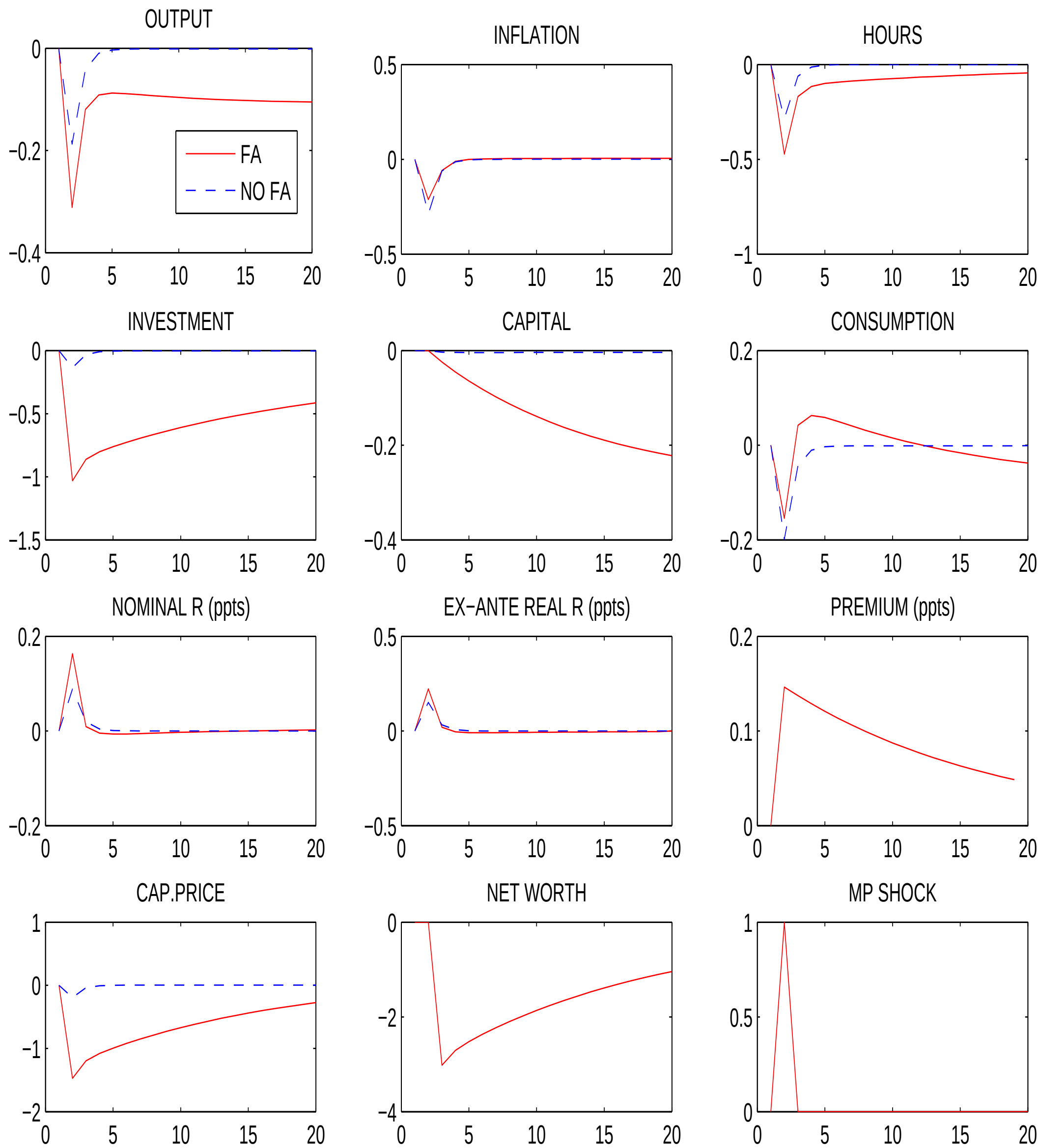


Figure 2: Technology shock

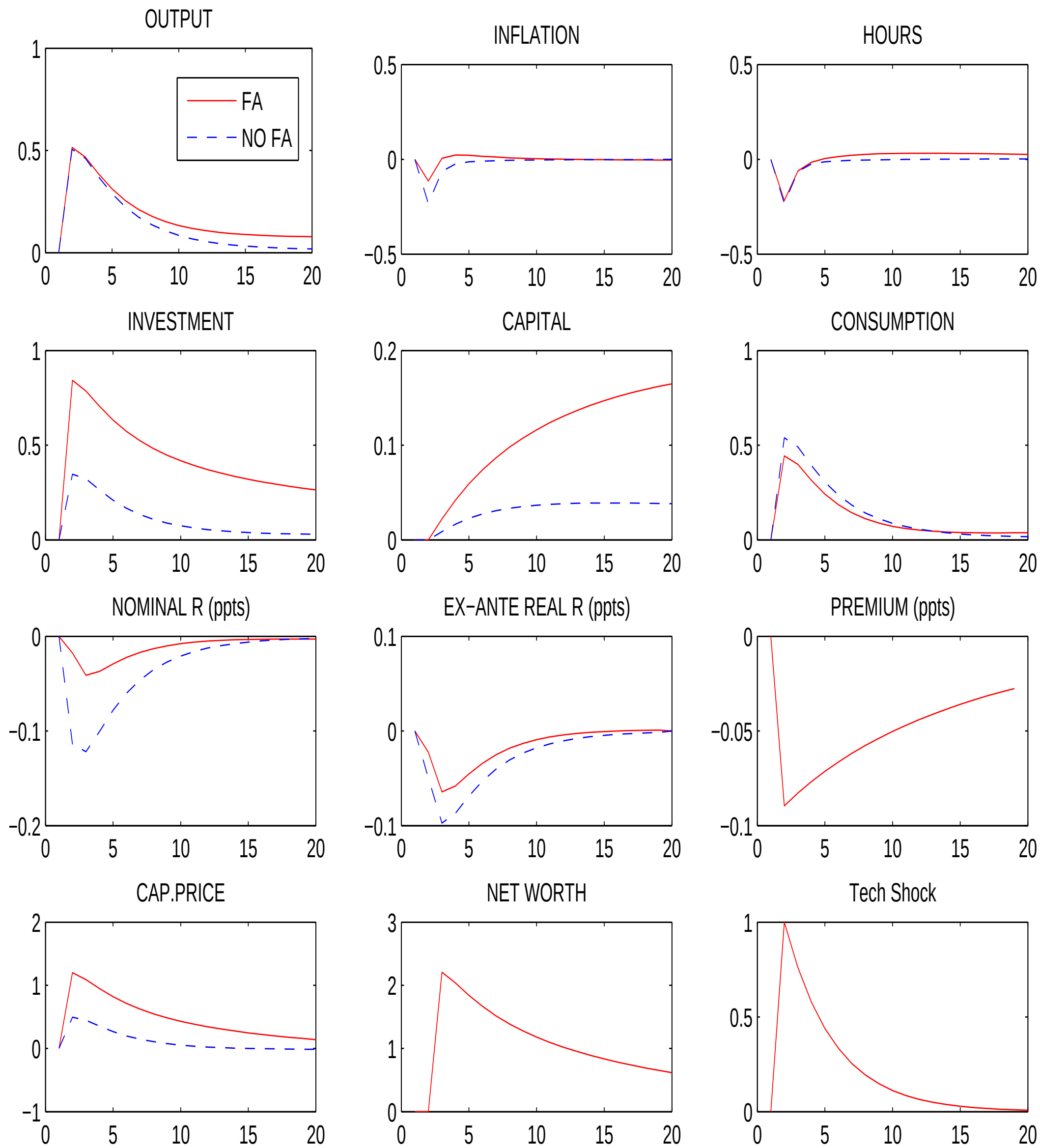


Figure 3: Money demand shock

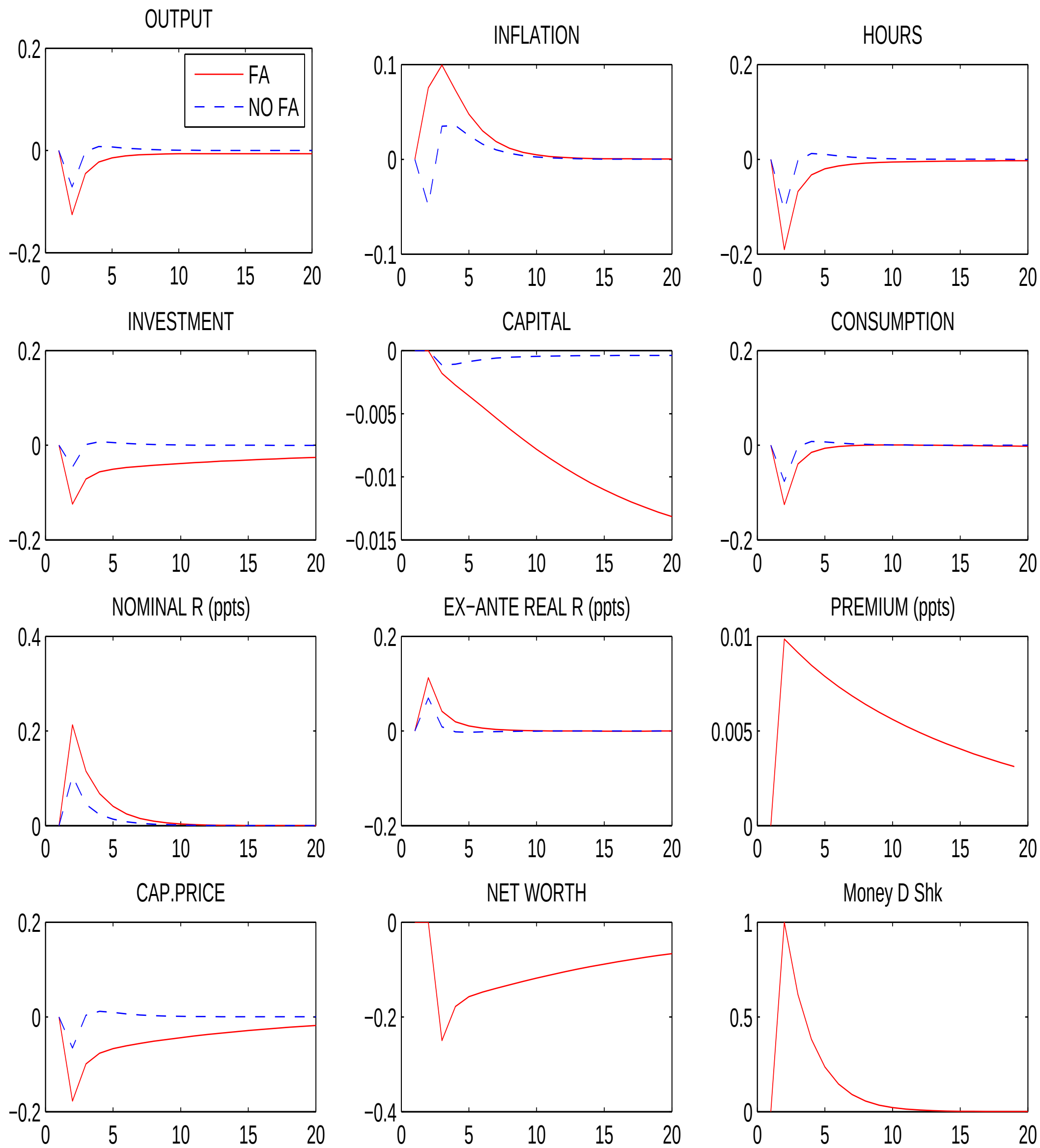


Figure 4: Preference shock

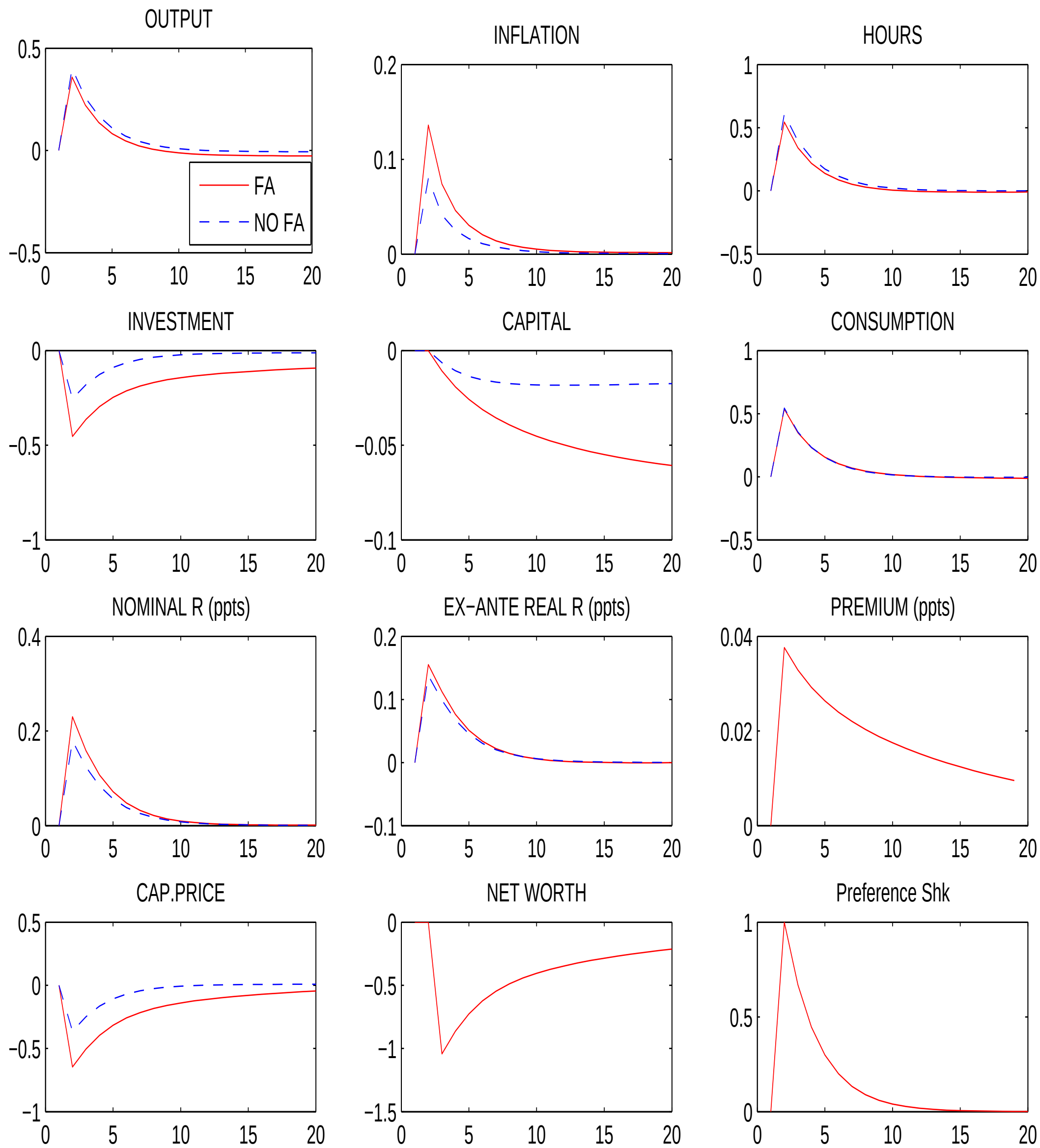


Figure 5: Investment efficiency shock

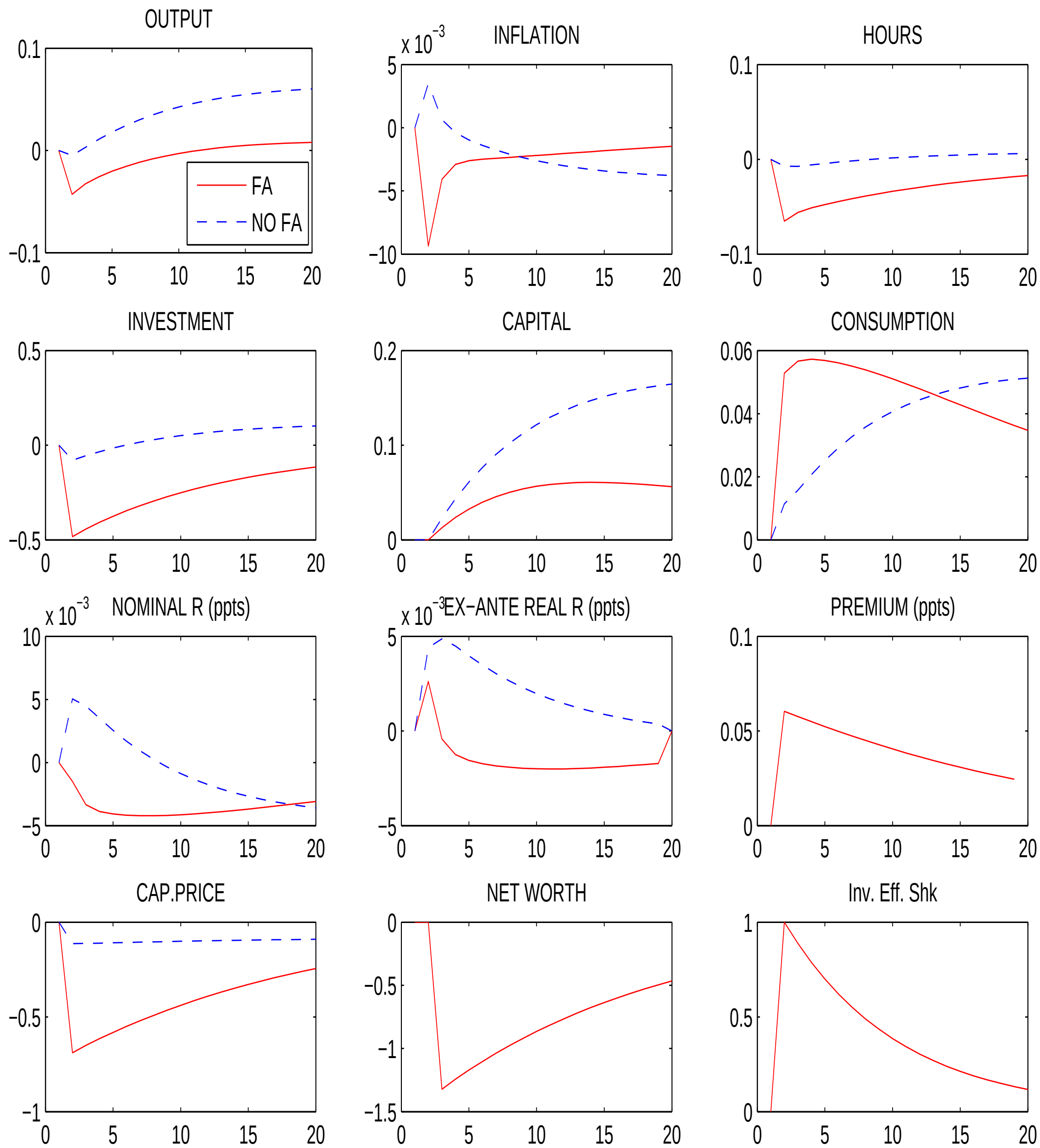
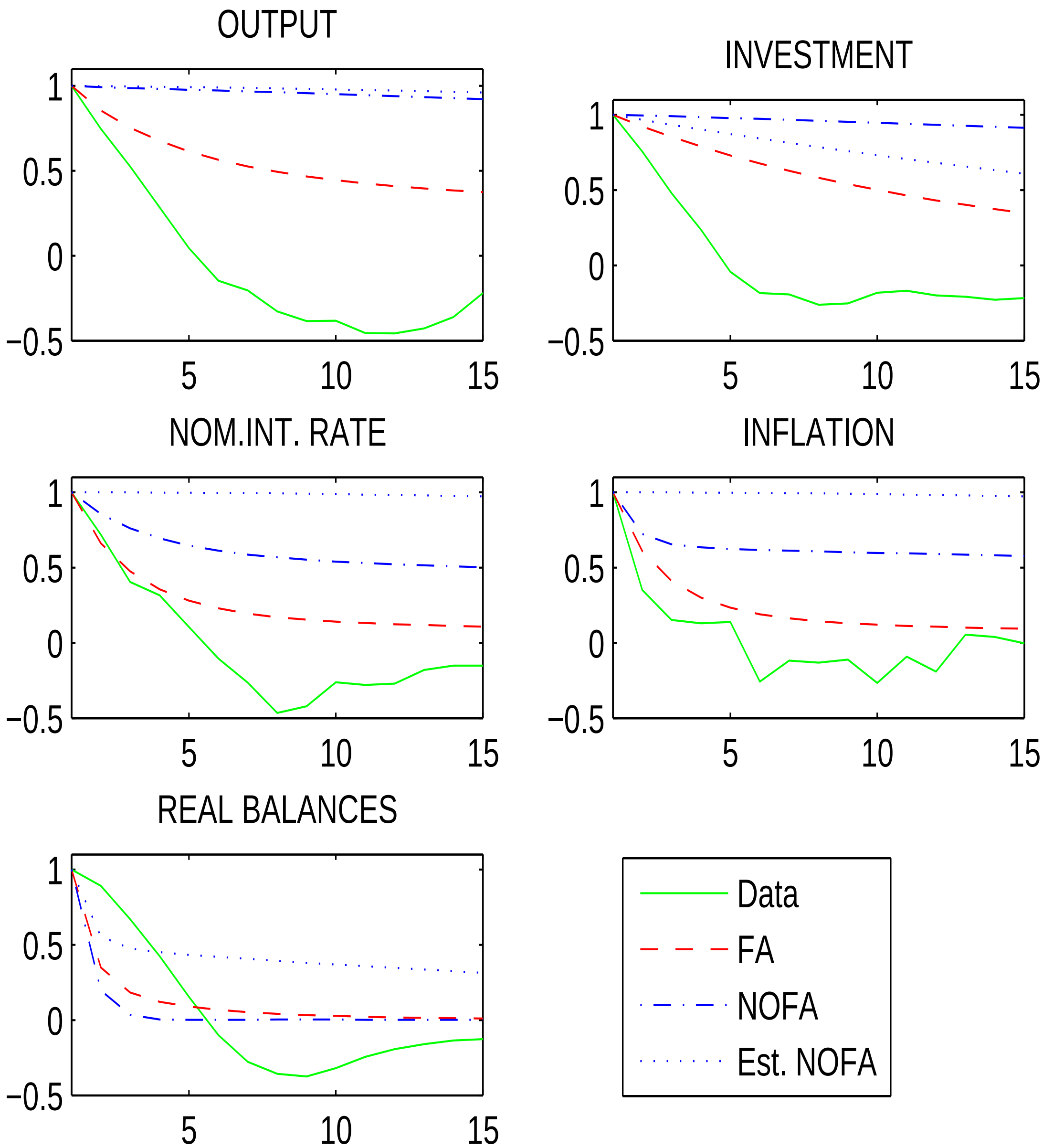


Figure 6: Autocorrelations



A. The non-linear equilibrium system

$$\frac{z_t c_t^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + b_t^{1/\gamma} m_t^{\frac{\gamma-1}{\gamma}}} = \lambda_t; \tag{A.1}$$

$$\left(\frac{b_t c_t}{m_t}\right)^{1/\gamma} = \frac{R_t^n - 1}{R_t^n}; \tag{A.2}$$

$$\frac{\eta}{1-h_t} = \lambda_t w_t; \tag{A.3}$$

$$\frac{1}{R_t^n} = \beta E_t \left[\frac{\lambda_{t+1}}{\pi_{t+1}\lambda_t}\right]; \tag{A.4}$$

$$R_t = E_t \left[\frac{R_t^n}{\pi_{t+1}}\right]; \tag{A.5}$$

$$r_{kt} = \alpha \frac{y_t}{k_t} mc_t; \tag{A.6}$$

$$w_t = (1-\alpha)\frac{y_t}{h_t} mc_t; \tag{A.7}$$

$$y_t = k_t^{\alpha} \left(A_t h_t\right)^{1-\alpha}; \tag{A.8}$$

$$y_t = c_t + i_t; \tag{A.9}$$

$$\bar{p}_t = \frac{\theta}{\theta-1} \frac{E_t \sum_{l=0}^{\infty} (\beta\phi)^l \lambda_{t+l} mc_{t+l} y_{t+l}/p_{t+l}}{E_t \sum_{l=0}^{\infty} (\beta\phi)^l \lambda_{t+l} y_{t+l}/p_{t+l}}; \tag{A.10}$$

$$p_t^{1-\theta} = \phi p_{t-1}^{1-\theta} + (1-\phi)\bar{p}_t^{1-\theta}; \tag{A.11}$$

$$E_t f_{t+1} = E_t \left[\left(\frac{n_{t+1}}{q_t k_{t+1}}\right)^{-\psi} R_t\right]; \tag{A.12}$$

$$E_t f_{t+1} = E_t \left[\frac{r_{kt+1} + (1-\delta) q_{t+1}}{q_t}\right]; \tag{A.13}$$

$$E_t n_{t+1} = \nu \left[f_t q_{t-1} k_t - E_{t-1} f_t (q_{t-1} k_t - n_t)\right] + (1-\nu) g_t; \tag{A.14}$$

$$k_{t+1} = x_t i_t + (1-\delta) k_t; \tag{A.15}$$

$$q_t = 1 + \chi \left(\frac{i_t}{k_t} - \delta\right); \tag{A.16}$$

$$\frac{R_t^n}{R^n} = \left(\frac{R_{t-1}^n}{R^n}\right)^{\varrho_R} \left(\frac{\pi_t}{\pi}\right)^{\varrho_\pi} \left(\frac{y_t}{y}\right)^{\varrho_y} \left(\frac{\mu_t}{\mu}\right)^{\varrho_\mu} \exp(\varepsilon_R); \tag{A.17}$$

$$\mu_t = m_t \pi_t / m_{t-1}. \tag{A.18}$$

B. The steady-state equilibrium

$$\mu = \pi = 1; \tag{B.1}$$

$$q = 1; \tag{B.2}$$

$$mc = \frac{\theta - 1}{\theta}; \tag{B.3}$$

$$R = R^n = 1/\beta; \tag{B.4}$$

$$f = r_k + 1 - \delta; \tag{B.5}$$

$$f = S(\cdot)R; \tag{B.6}$$

$$i = \delta k; \tag{B.7}$$

$$\lambda c = \left[1 + b\left(\frac{\pi}{\pi - \beta}\right)^{\gamma - 1}\right]^{-1}; \tag{B.8}$$

$$\lambda m = \lambda c b\left(\frac{\pi}{\pi - \beta}\right)^{\gamma}; \tag{B.9}$$

$$\frac{k}{y} = \frac{\alpha mc}{r_k}; \tag{B.10}$$

$$\frac{c}{y} = 1 - \delta\frac{k}{y} \tag{B.11}$$

$$wh\lambda = \frac{(1-\alpha)(\lambda c)mc}{c/y}; \tag{B.12}$$

$$h = \frac{wh\lambda}{\eta + wh\lambda}; \tag{B.13}$$

$$y = Ah\left(\frac{k}{y}\right)^{\alpha/(1-\alpha)}; \tag{B.14}$$

$$\frac{n}{k} = \frac{1}{1 - \gamma S(\cdot)R}\left(\frac{g}{k}\right). \tag{B.15}$$

C. The log-linearized equilibrium system

Static equations

$$((1-\gamma)\,\lambda c - 1)\,\hat{c}_t = \gamma\hat{\lambda}_t + \lambda\frac{(R^n-1)}{R^n}m\left(\hat{b}_t + (\gamma-1)\,\hat{m}_t\right) - \gamma\hat{z}_t; \tag{C.1}$$

$$\hat{b}_t + \hat{c}_t - \hat{m}_t = \gamma\frac{1}{(R^n-1)}\hat{R^n}_t; \tag{C.2}$$

$$h\hat{h}_t/(1-h) - \hat{w}_t = \hat{\lambda}_t; \tag{C.3}$$

$$\hat{y}_t = \hat{A}_t + \alpha\hat{k}_t + (1-\alpha)\hat{h}_t; \tag{C.4}$$

$$y\hat{y}_t = c\hat{c}_t + i\hat{i}_t; \tag{C.5}$$

$$\hat{w}_t = \hat{y}_t + \hat{mc}_t - \hat{h}_t; \tag{C.6}$$

$$\hat{r}_{kt} = \hat{y}_t + \hat{mc}_t - \hat{k}_t; \tag{C.7}$$

$$\hat{\mu}_t = \hat{m}_t - \hat{m}_{t-1} + \hat{\pi}_t \tag{C.8}$$

$$\hat{R}^n_t = \varrho_R\hat{R^n}_{t-1} + \varrho_\pi\hat{\pi}_t + \varrho_\mu\hat{\mu}_t + \varrho_y\hat{y}_t + \varepsilon_{Rt}; \tag{C.9}$$

$$\hat{f}_t + \hat{q}_{t-1} = \frac{r_k}{f}\hat{r}_{kt} + \frac{1-\delta}{f}\hat{q}_t; \tag{C.10}$$

$$\hat{q}_t = \chi(\hat{i}_t - \hat{k}_t). \tag{C.11}$$

Dynamic equations

$$\beta\hat{\pi}_{t+1} = \hat{\pi}_t - \frac{(1-\beta\phi)(1-\phi)}{\phi}\hat{mc}_t; \tag{C.12}$$

$$\hat{\lambda}_{t+1} = \hat{\lambda}_t - \hat{R}_t; \tag{C.13}$$

$$\hat{\pi}_{t+1} = \hat{R}_t^n - \hat{R}_t; \tag{C.14}$$

$$\hat{k}_{t+1} = \delta\hat{i}_t + \delta\hat{x}_t + (1-\delta)\hat{k}_t; \tag{C.15}$$

$$\hat{f}_{t+1} + \psi\hat{n}_{t+1} - \psi\hat{k}_{t+1} = \hat{R}_t + \psi\hat{q}_t; \tag{C.16}$$

$$\frac{\hat{n}_{t+1}}{\nu f} = \frac{k}{n}\hat{f}_t - \left(\frac{k}{n} - 1\right)\left(\hat{R}_{t-1}^n - \hat{\pi}_t\right) - \psi\left(\frac{k}{n} - 1\right)(\hat{k}_t + \hat{q}_{t-1}) + \cdots$$
$$+ \left(\psi(\frac{k}{n} - 1) + 1\right)\hat{n}_t. \tag{C.17}$$