INVESTMENT SHOCKS AND BUSINESS CYCLES

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Abstract. Shocks to the marginal efficiency of investment are the most important drivers of business cycle fluctuations in US output and hours. Moreover, these disturbances drive prices higher in expansions, like a textbook demand shock. We reach these conclusions by estimating a DSGE model with several shocks and frictions. We also find that neutral technology shocks are not negligible, but their share in the variance of output is only around 25 percent, and even lower for hours. Finally, we show that imperfect competition and technological frictions are key to the transmission of investment shocks in our model.

1. Introduction

What is the source of economic fluctuations? This is one of the defining questions of modern dynamic macroeconomics, at least since Sims (1980) and Kydland and Prescott (1982). Yet, the literature is far from a consensus on the right answer. On the one hand, the work that approaches the question from the perspective of general equilibrium models tends to attribute a dominant role in business cycles to neutral technology shocks (for example Prescott (1986), Cooley and Prescott (1995) or King and Rebelo (1999)). On the other hand, the structural VAR literature usually points at other disturbances as the main sources of business cycles, and rarely finds that technology shocks explain more than one quarter of output fluctuations (see, for instance, Shapiro and Watson (1988), King, Plosser, Stock, and Watson (1991), Cochrane (1994), Gali (1999) or Fisher (2006)).

This paper confirms the SVAR evidence, but it does so from the perspective of a fully articulated dynamic stochastic general equilibrium (DSGE) model. Our main finding is that shocks to the marginal efficiency of investment are the most important drivers of macroeconomic fluctuations. These shocks, often called investment specific technology shocks, affect the yield of a foregone unit of consumption in terms of its contribution to tomorrow's capital input. For simplicity, we label these shocks as *investment shocks*.

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Our conclusion about the importance of investment shocks is based on the Bayesian estimation of a medium scale model of the business cycle that includes a rich set of nominal and real rigidities, along the lines of Christiano, Eichenbaum, and Evans (2005). As in Smets and Wouters (2007), several shocks can potentially play a role for fluctuations in our model. Among them, a neutral technology shock, as in Kydland and Prescott (1982), an investment shock, as in Greenwood, Hercowitz, and Huffman (1988) and Greenwood, Hercowitz, and Krusell (2000), as well as a shock to labor supply, as in Hall (1997).

We find that the investment shock is the single most important source of business cycle fluctuations in the US post-war period. This disturbance explains between 50 and 60 percent of the fluctuations in output and hours and more than 80 percent of the fluctuations in investment. The contribution of the neutral technology shock is also non-negligible. Indeed, this shock explains about a quarter of the movements in output and consumption, although only about ten percent of those in hours. Moreover, this shock plays an important role in generating comovement between consumption on the one hand, and output and hours on the other, a feature of business cycles which the investment shock has some trouble generating.

In this respect, the neutral technology and the investment shocks play a complementary role in our model, with the former contributing a significant share of the comovement between output and consumption, and the latter mainly responsible for generating the overall volatility and comovement between output, investment and hours. Another aspect of this complementarity is that the two shocks can be fairly neatly characterized as a demand (the investment shock) and a supply (the neutral technology) shock, in the sense of generating positive and negative comovement between prices and quantities. As for the labor supply shock, we find that it is the dominant source of fluctuations in hours at very low frequencies, although not over the business cycle.

As emphasized by Barro and King (1984) and Greenwood, Hercowitz, and Huffman (1988), investment shocks are unlikely candidates to generate business cycles in standard neoclassical models. In fact, a positive shock to the marginal efficiency of investment increases the rate of return on capital, inducing an increase in labor and a decline in consumption. Moreover, since capital is fixed in the short run, labor productivity falls. These are not the main characteristics of business cycles, explaining why the DSGE literature has favored other disturbances, namely the neutral technological shock, as sources of fluctuations.

Our results are very different from the conventional view because our model exhibits a number of real and nominal rigidities that are generally absent in the neoclassical framework: habit formation in consumption, variable capital utilization, investment adjustment costs and imperfect competition and price stickiness in products and labor markets. These frictions[1] have been adopted by the existing literature to improve the empirical performance of monetary models (Christiano, Eichenbaum, and Evans (2005)). As it turns out, each of these frictions also play an important role in ameliorating the problems related to the propagation mechanism of the investment shocks typical of neoclassical models.

For example, we find that removing variable capital utilization or imperfect competition substantially reduces the ability of investment shocks to explain the business cycle. The intuition is simple: in response to a positive shock to the efficiency of new capital goods, utilization rises. This stimulates production and increases labor demand. As emphasized by Greenwood, Hercowitz, and Huffman (1988), this mechanism can generate a positive response of labor productivity and consumption to an investment shock.

In our model, the presence of monopolistic competition with sticky wages and prices drives an additional endogenous wedge between the marginal rate of substitution of consumption and leisure, and the marginal product of labor. For instance, in response to an investment shock and the consequent rise in the rate of return on capital, real marginal costs increase, or equivalently the equilibrium mark-up drops, which amplifies the positive shift in labor demand. This might contribute to generating a positive comovement between consumption and labor. In this respect, the endogenous price mark-up plays a similar role to utilization, since it acts as an shifter of labor demand.

Our results about the importance of investment shocks are consistent the SVAR findings of Fisher (2006) and Canova, Lopez-Salido, and Michelacci (2006), and broadly in line with the general equilibrium analysis of Greenwood, Hercowitz, and Krusell (2000). Differently from us, all of these studies use direct observations on the relative price of investment as a proxy for the investment specific technological shock. On the contrary, in our framework, the investment shock is treated as an unobservable process and is identified through its dynamic effects on the macroeconomic variables included in the estimation, according to the

[1] For simplicity, we refer to all of these features of the model as "frictions." It is clear, however, that some of these features can hardly be thought of as frictions in the literal sense of the word.

restrictions implied by the DSGE model.[2] This empirical strategy might be better suited to capture sources of variation in the marginal efficiency of investment that are not fully reflected in the variability of the relative price of investment to consumption. For instance, this could be the case for shocks to financial frictions (Bernanke, Gertler, and Gilchrist (1999)).

This paper is also related to a recent literature on the estimation of medium and large scale DSGE models (see, for instance, Altig, Christiano, Eichenbaum, and Linde (2005), Del Negro, Schorfheide, Smets, and Wouters (2007), Gertler, Sala, and Trigari (2007), Justiniano and Primiceri (2007) or Smets and Wouters (2007)). We share with this literature the basic structure of the theoretical framework. However, we differ from these papers in two important respects, which also highlight the contribution of our analysis. First, we focus on the specific question about the sources of business cycle fluctuations, and emphasize the predominant role of investment shocks. Second, we carefully investigate how some of the frictions typically included in modern DSGE models contribute to diminish the role of neutral technology shocks in fluctuations, compared to the Real Business Cycle benchmark.

The rest of the paper is organized as follows. Section 2 illustrates the theoretical model. Section 3 describes the approach to inference and discusses the fit of the model. Section 4 and 5 present the main result about the importance of investment shocks. Section 6 conducts a series of robustness check, while section 7 concludes.

2. The Model Economy

This section outlines our baseline model of the U.S. business cycle. This is a medium-scale DSGE model, with a host of nominal and real frictions, along the lines of Christiano, Eichenbaum, and Evans (2005). The model fits the data well, which is not surprising in light of the evidence presented in Del Negro, Schorfheide, Smets, and Wouters (2007) and Smets and Wouters (2007).[3]

The model economy is populated by five classes of agents. Producers of final goods, which "assemble" a continuum of intermediate goods produced by monopolistic intermediate goods producers. Households, who consume the final good, accumulate capital, and supply

[2] In this respect, our strategy is similar to Fisher (1997), which infers the properties of technological progress in the investment sector through a GMM strategy applied to macroeconomic quantities.

[3] We experimented with a number of variants of the baseline model. These robustness checks are reported in section 6.

differentiated labor services to competitive "employment agencies". A Government. We present their optimization problems in turn.

2.1. **Final goods producers.** At every point in time t, perfectly competitive firms produce the final consumption good Y_t, combining a continuum of intermediate goods $Y_t(i)$, $i \in [0,1]$ according to the technology

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{1}{1+\lambda_{p,t}}} di \right]^{1+\lambda_{p,t}}.$$

$\lambda_{p,t}$, follows the exogenous stochastic process

$$\log \lambda_{p,t} = (1-\rho_p) \log \lambda_p + \rho_p \log \lambda_{p,t-1} + \varepsilon_{p,t} - \theta_p \varepsilon_{p,t-1},$$

where $\varepsilon_{p,t}$ is $i.i.d.N(0, \sigma_p^2)$. This process represents a disturbance to the desired mark-up of prices over marginal costs for intermediate firms. For simplicity, we label this shock as *price mark-up shock*. As in Smets and Wouters (2007), the ARMA(1,1) structure helps capturing the moving average, high frequency component of inflation. Profit maximization and the zero profit condition imply the following relationship between the price of the final good, P_t, and the prices of the intermediate goods, $P_t(i)$

$$P_t = \left[\int_0^1 P_t(i)^{\frac{1}{\lambda_{p,t}}} di \right]^{\lambda_{p,t}},$$

and the demand function for the intermediate good i

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t.$$

2.2. **Intermediate goods producers.** A monopolist produces the intermediate good i according to the production function

$$Y_t(i) = \max \left\{ A_t^{1-\alpha} K_t(i)^\alpha L_t(i)^{1-\alpha} - A_t F; 0 \right\},$$

where $K_t(i)$ and $L_t(i)$ denote the capital and labor inputs for the production of good i and F represents a fixed cost of production. A_t is an exogenous stochastic process capturing the effects of technology, whose growth rate ($z_t \equiv \Delta \log A_t$) evolves according to

$$z_t = (1-\rho_z)\gamma + \rho_z z_{t-1} + \varepsilon_{z,t},$$

where $\varepsilon_{z,t}$ is $i.i.d.N(0, \sigma_z^2)$. Therefore, the level of technology is non stationary.

As in Calvo (1983), a fraction ξ_p of firms cannot re-optimize their prices and, therefore, set their prices following the indexation rule

$$P_t(i) = P_{t-1}(i)\pi_{t-1}^{\iota_p}\pi^{1-\iota_p},$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$ and π denotes the steady state value of π_t. On the other hand, re-optimizing firms choose their price, $\tilde{P}_t(i)$, by maximizing the present value of future profits, subject to the usual cost minimization condition,

$$E_t \sum_{s=0}^{\infty} \xi_p^s \beta^s \lambda_{t+s} \left\{ \left[\tilde{P}_t(i) \left(\Pi_{j=0}^{s} \pi_{t-1+j}^{\iota_p} \pi^{1-\iota_p} \right) \right] Y_{t+s}(i) - \left[W_t L_t(i) + r_t^k K_t(i) \right] \right\},$$

where λ_{t+s} is the marginal utility of consumption, and W_t and r_t^k denote the nominal wage and the rental rate of capital.

2.3. **Employment agencies.** Firms are owned by a continuum of households, indexed by $j \in [0,1]$. As in Erceg, Henderson, and Levin (2000), each household is a monopolistic supplier of specialized labor, $L_t(j)$. A large number of "employment agencies" combines this specialized labor into labor services available to the intermediate firms, according to

$$L_t = \left[\int_0^1 L_t(j)^{\frac{1}{1+\lambda_{w,t}}} dj \right]^{1+\lambda_{w,t}}.$$

$\lambda_{w,t}$ follows the exogenous stochastic process

$$\log \lambda_{w,t} = (1-\rho_w)\log \lambda_w + \rho_w \log \lambda_{w,t-1} + \varepsilon_{w,t} - \theta_w \varepsilon_{w,t-1},$$

where $\varepsilon_{w,t}$ is $i.i.d.N(0,\sigma_w^2)$. This shock is a disturbance to the desired mark-up of the wage over the marginal rate of substitution for wage setters. For simplicity, we label this shock as *wage mark-up shock*. It plays a similar role to the "labor supply" shock present in the analysis of Hall (1997), Del Negro, Schorfheide, Smets, and Wouters (2007) or Justiniano and Primiceri (2007).[4] Profit maximization and the zero profit condition for the perfectly competitive employment agencies imply the following relationship between the wage paid by the intermediate firms and the wage received by the supplier of labor of type j, $W_t(j)$

$$W_t = \left[\int_0^1 W_t(j)^{\frac{1}{\lambda_{w,t}}} dj \right]^{\lambda_{w,t}},$$

and the labor demand function

$$L_t(j) = \left(\frac{W_t(j)}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} L_t.$$

[4] The two shocks would be observationally equivalent if we did not have the output gap in the policy rule.

2.4. **Households.** Each household maximizes the utility function

$$E_t \sum_{s=0}^{\infty} \beta^s b_{t+s} \left[\log \left(C_{t+s} - h C_{t+s-1} \right) - \varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu} \right],$$

where C_t is consumption, h is the "degree" of habit formation and b_t is a "discount factor" shock affecting both the marginal utility of consumption and the marginal disutility of labor.[5] This shock follows the stochastic processes

$$\log b_t = \rho_b \log b_{t-1} + \varepsilon_{b,t},$$

with $\varepsilon_{b,t} \sim i.i.d. N(0, \sigma_b^2)$. Note that we work with log utility to ensure the existence of a balanced growth path, as in the real business cycle tradition. Moreover, consumption is not indexed by j because the existence of state contingent securities ensures that in equilibrium consumption and asset holdings are the same for all households.

The household's budget constraint is

$$P_t C_t + P_t I_t + T_t + B_t \leq R_{t-1} B_{t-1} + Q_{t-1}(j) + \Pi_t + W_t(j) L_t(j) + r_t^k u_t \bar{K}_{t-1} - P_t a(u_t) \bar{K}_{t-1},$$

where I_t is investment, T_t are lump-sum taxes, B_t is holdings of government bonds, R_t is the gross nominal interest rate, $Q_t(j)$ is the net cash flow from participating in state contingent securities, and Π_t is the per-capita profit accruing to households from ownership of the firms.

Households own capital and choose the capital utilization rate, u_t, which transforms physical capital into effective capital according to

$$K_t = u_t \bar{K}_{t-1}.$$

Effective capital is then rented to firms at the rate r_t^k. The cost of capital utilization is $a(u_t)$ per unit of physical capital. As in Altig, Christiano, Eichenbaum, and Linde (2005), we assume that $u_t = 1$ and $a(u_t) = 0$ in steady state. In our log-linear approximation of the model solution, we only need to specify the curvature of the function a in steady state, $\chi \equiv \frac{a''(1)}{a'(1)}$. The physical capital accumulation equation is

$$\bar{K}_t = (1-\delta) \bar{K}_{t-1} + \mu_t \left(1 - S \left(\frac{I_t}{I_{t-1}} \right) \right) I_t,$$

where δ denotes the depreciation rate. The function S captures the presence of adjustment costs in investment, as in Christiano, Eichenbaum, and Evans (2005) and Altig, Christiano,

[5] We assume a cashless limit economy as described in Woodford (2003).

Eichenbaum, and Linde (2005). We assume that S and $S' = 0$, and $S'' > 0$ in steady state.[6] Following Greenwood, Hercowitz, and Krusell (1997) and Fisher (2006), μ_t can be interpreted as an investment specific technology shock affecting the efficiency with which consumption goods are transformed into capital. For simplicity, we label this shock as the *investment shock.* We assume that it follows the exogenous process

$$\log \mu_t = \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu,t},$$

where $\varepsilon_{\mu,t}$ is $i.i.d.N(0, \sigma_\mu^2)$.

As in Erceg, Henderson, and Levin (2000), a fraction ξ_w of households cannot re-optimize their wages and, therefore, set them according to the indexation rule

$$W_t(j) = W_{t-1}(j) \left(\pi_{t-1} e^{z_{t-1}}\right)^{\iota_w} \left(\pi e^{\gamma}\right)^{1-\iota_w}.$$

The remaining fraction of re-optimizing households maximizes instead

$$E_t \sum_{s=0}^{\infty} \xi_w^s \beta^s b_{t+s} \left\{ -\varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu} \right\},$$

subject to the labor demand function.

2.5. **Government.** Monetary policy sets short term nominal interest rates following a Taylor type rule of the form

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{Y_t}{Y_t^*}\right)^{\phi_Y} \right]^{1-\rho_R} \left[\frac{Y_t / Y_{t-1}}{Y_t^* / Y_{t-1}^*} \right]^{\phi_{dY}} \eta_{mp,t},$$

where R is the steady state for the nominal interest rate. Following Smets and Wouters (2007), monetary policy is assumed to respond to deviations of inflation from the steady state, and to the level and the growth rate of the output gap (Y_t/Y_t^*).[7] The monetary policy rule is also perturbed by a monetary policy shock, $\eta_{mp,t}$, which evolves according to

$$\log \eta_{mp,t} = \rho_{mp} \log \eta_{mp,t-1} + \varepsilon_{mp,t},$$

where $\varepsilon_{mp,t}$ is $i.i.d.N(0, \sigma_{mp}^2)$.

Fiscal policy is fully Ricardian: the Government finances its budget deficit by issuing short term bonds. Public spending is determined exogenously as a time-varying fraction of GDP

$$G_t = \left(1 - \frac{1}{g_t}\right) Y_t,$$

[6] Lucca (2005) shows that this formulation of the adjustment cost function is equivalent (up to first order) to a generalization of the time to build assumption.

[7] The output gap is defined as the difference between output and flexible price output (Woodford (2003)).

where g_t is a disturbance following the stochastic process

$$\log g_t = (1 - \rho_g) \log g + \rho_g \log g_{t-1} + \varepsilon_{g,t},$$

with $\varepsilon_{g,t} \sim i.i.d.N(0, \sigma_g^2)$.

2.6. **Market clearing.** The aggregate resource constraint,

$$C_t + I_t + G_t + a(u_t)\bar{K}_{t-1} = Y_t,$$

can be derived by combining the Government and the households' budget constraints with the zero profit condition of the final goods producers and the employment agencies.

2.7. **Model solution.** In this model, consumption, investment, capital, real wages and output evolve along a stochastic balanced growth path, since the technology process A_t has a unit root. Therefore, in order to solve the model, we first rewrite it in terms of detrended variables, compute the non-stochastic steady state of the transformed model, and then log-linearly approximate it around this steady state.

3. Bayesian Inference

3.1. **Data and priors.** We estimate the model using

$$[\Delta \log Y_t, \Delta \log C_t, \Delta \log I_t, \log L_t, \Delta \log \frac{W_t}{P_t}, \pi_t, R_t] \tag{3.1}$$

as the vector of observable variables, where Δ denotes the temporal difference operator. We use quarterly data and our dataset covers the period from 1954QIII to 2004QIV. A precise description of the data series used in the estimation can be found in appendix A.

We use Bayesian methods to characterize the posterior distribution of the structural parameters of the model (see An and Schorfheide (2007) for a survey). The posterior distribution combines the likelihood function with prior information.[8] In the rest of this section we briefly discuss the assumptions about the prior.

We fix a small number of parameters to values commonly used in the literature. In particular, we set the quarterly depreciation rate of capital (δ) to 0.025 and the steady state government spending to GDP ratio ($1 - 1/g$) to 0.22, which corresponds to the average value of G_t/Y_t in our sample. Table 1 reports the priors for the remaining parameters of the model.

[8] In section 6 we show that results are robust to estimating the model by maximum likelihood (flat priors).

While these priors are relatively disperse and broadly in line with those adopted in previous studies (Del Negro, Schorfheide, Smets, and Wouters (2007) or Justiniano and Primiceri (2007)), some of them deserve a brief discussion.

For all but two persistence parameters we use a Beta prior, with mean 0.6 and standard deviation 0.2. One of the two exceptions is neutral technology, which already includes a unit root. For this reason, the prior for the autocorrelation of its growth rate (ρ_z) is centered at 0.4 instead. We use 0.4 also to center the prior for the persistence of the monetary policy shocks, because the policy rule already allows for interest rates inertia. The covariance matrix of the innovations is assumed to be diagonal. The intertemporal preference, price and wage mark-up shocks are normalized to enter with a unity coefficients in the consumption, price inflation and wage equations respectively (see Smets and Wouters (2007) and appendix B). The priors on the innovations' standard deviations are quite disperse and chosen in order to generate volatilities for the endogenous variables broadly in line with the data.

As opposed to commenting on the prior for specific coefficients, we evaluate all the priors on the exogenous processes and the structural parameters indirectly, by analyzing their implications for the unconditional variance decomposition of the observable variables of the model. Table 2 makes clear that our prior beliefs are in line with the traditional RBC view: the variability of output, consumption, investment and hours is due for the most part to neutral technological disturbances. According to our prior-based variance decomposition, the investment shock is the least important shock.

3.2. **Parameter estimates.** In table 1, we report the estimates of the model's parameters. We present posterior medians, standard deviations and 90 percent posterior intervals. In line with previous studies, we estimate a substantial degree of price and wage stickiness, habit formation in consumption and adjustment costs in investment (see, for instance, Altig, Christiano, Eichenbaum, and Linde (2005), Del Negro, Schorfheide, Smets, and Wouters (2007) or Smets and Wouters (2007)).

As in Del Negro, Schorfheide, Smets, and Wouters (2007) and Justiniano and Primiceri (2007), capital utilization is not very elastic: in response to a 1 percent positive change in the rental rate of capital, utilization increases by slightly less than 0.2 percent.

Similar to Smets and Wouters (2007), our estimates of the share of capital income (α) and the Frisch elasticity of labor supply ($1/\nu$) are both lower than the values typically adopted in the RBC literature. However, as we show in section 6, none of our results depend crucially on these estimates of α and ν. We investigate the empirical performance of the model in the next subsection.

3.3. **Model fit.** Given our posterior estimates, how well does the model fit the data? In this section, we address this question by comparing a set of statistics implied by the model to those measured in the data. In particular, we study the standard deviation and the complete correlation structure of the observable variables included in the estimation.

Table 3 reports the model-implied standard deviation of our seven observable variables, as well as the standard deviation of these variables relative to output growth. We also report 90 percent probability intervals that account for both parameter uncertainty and small sample uncertainty. Relative to the data, the model overpredicts a bit the volatility of output growth, but approximately matches the relative standard deviations of consumption, investment growth and hours. There is also a tendency to underpredict the volatility of nominal interest rates and inflation, which might be due to the fact that the model captures only part of the very high correlation between these two variables.

Why does not the model capture perfectly the standard deviation of the observable variables? This is due to the discipline imposed by the likelihood-based estimation procedure, that strikes a balance between matching standard deviations and other moments in the data like, for instance, autocorrelations and cross-correlations. Following Gertler, Sala, and Trigari (2007), figure 1 displays the full matrix of cross-correlations of the observable variables in the data (grey line) and in the model (back line). We also report the 90 percent posterior intervals implied by parameter uncertainty and small sample uncertainty.

Focus first on the upper-left 4-by-4 block of the matrix, which includes all the quantities in the model. On the diagonal, we see that the model captures the decaying autocorrelation structure of these four variables very well. The success is particularly impressive for hours, for which the model-implied and data autocorrelations lay virtually on top of each other. In terms of cross-correlations, the model does extremely well for output (the first row and column) and for hours (the fourth row and column), but fails to capture the contemporaneous correlation between consumption and investment growth. This correlation is slightly positive in the data, but essentially zero in the model.[9]

[9] The cross-correlation between consumption and investment improves when we use a non-separable utility function in consumption and leisure. We will return to this point in section 6.

In sum, relative to smaller scale RBC models (e.g. Cooley and Prescott (1995) or King and Rebelo (1999)), we probably do less well in matching the properties of consumption. However, our model performs considerably better in terms of hours worked. This is important because one of our main objectives is investigating the sources of business cycle fluctuations in hours.

With respect to prices, the model is overall quite successful in reproducing the main stylized facts. We emphasize two issues: first, the model struggles to capture the full extent of the persistence of inflation and the nominal interest rate, even in the presence of inflation indexation and of a fairly high smoothing parameter in the interest rate rule. Second, we match very closely the correlation between output and inflation, which is highlighted for example by Smets and Wouters (2007) as an important measure of the model's empirical success.

4. Shocks and Business Cycles

In this section, we present and elaborate on the main result of the paper: investment shocks are the most important source of fluctuations. First, we document the quantitative extent of this basic fact, by looking at the variance decomposition for output, hours and other macroeconomic variables. Second, we provide some intuition for the result by studying the impulse responses to the main shocks in the model. This exercise also allows us to informally discuss how those shocks are identified by our empirical procedure.

4.1. **Variance decomposition.** Table 4 reports the contribution of each shock to the unconditional variance of the *observable* variables of the model. From the first row of the table, we see that investment shocks account for more than 50 percent of the fluctuations in the growth rate of output, by far the largest contribution. The importance of investment shocks for output growth is even more evident in figure 2, where we plot GDP growth data and the counterfactual evolution of GDP growth when we feed only the estimated investment shocks and shut down the remaining disturbances. Clearly, the two lines track each other quite closely.

Looking at the other shocks and variables, two results stand out. First, the neutral technology shock retains a non-negligible role in our estimates, explaining around one quarter of the volatility of output, consumption and real wages. Second, the wage mark-up shock, which in the model is similar to Hall's (1997) labor supply shock, has a very important role in the fluctuations of wages, inflation and especially hours, explaining between one half and two thirds of their volatility.

The variance decomposition of hours is perhaps the most puzzling aspect of table 4. The investment shock explains only 20 percent of the movements in hours, less than half its contribution to output growth. Yet, the comovement of hours and output is one of the defining features of the business cycle. Table 5 sheds some light on this puzzle, by focusing on fluctuations in the *level* of all variables at business cycle frequencies.[10]

At business cycle frequencies, investment shocks explain approximately 60 percent of the fluctuations in hours, as well as 50 percent of those in output and more than 80 percent of those in investment. These results further strengthen the case for viewing investment shocks as the leading source of business cycle fluctuations, a results consistent with Fisher (2006). Notice, however, that investment shocks explain only a small fraction of the variability of consumption, for reasons that will be clear from the impulse response analysis in the next section.

Another interesting result emerging from the comparison of tables 4 and 5 is that the role of wage mark-up shocks virtually disappears at business cycle frequencies, retaining marginal explanatory power only for real wages and inflation. Figure 3 plots the share of the variance of hours explained by the wage mark-up shock, as a function of the spectrum frequencies. Business cycles correspond to a frequency range between 0.19 to 1. Clearly, wage mark-up shocks are important for hours only at very low frequencies.

4.2. **Model dynamics and shock identification.** Our main result is that the contribution of investment shocks to macroeconomic fluctuations is large, especially at business cycle frequencies. But what properties of this and the other shocks allow us to separately identify their contributions? This section provides some intuition for how this identification is possible, by studying the impulse responses of several key variables in the model. In particular, we focus on the responses to the three shocks that are responsible for the bulk of fluctuations, namely the investment shock, the neutral technology shock and the wage mark-up (or labor supply) shock.

[10] We compute the spectral density implied by the DSGE model, appropriately transformed to obtain the spectrum of the *level* of output, consumption, investment and wages. We define the business cycle frequencies as those corresponding to periodic components with cycles between 6 and 32 quarters, as in Stock and Watson (1999).

In response to a positive investment shock (figure 4), output, hours, investment, real wages and labor productivity all rise persistently and in a hump-shaped pattern. The reaction in investment is contemporaneous and roughly proportional to that in output, but much larger, by a factor between four and five. This factor is close to the ratio of the unconditional volatilities of the two series, which explains why the investment shock is able to account for most of the fluctuations in both output and investment. On the other hand, notice that consumption rises only with a delay of a few quarters. This explains why the investment shock does not account well for the comovement between investment and consumption, and for the bulk of fluctuations in consumption.

The reaction in hours is also fairly large, with a very similar profile to that of output. Moreover, the increase in hours is not associated with a drop in labor productivity, a fairly common implication of neoclassical models (Greenwood, Hercowitz, and Huffman (1988)). In our model, the procyclicality of labor productivity in response to investment shocks is the combined result of the endogeneity of capital utilization and imperfect competition in product markets. After an investment shock, utilization (not reported) rises because new capital is more productive and relatively cheaper (as in Greenwood, Hercowitz, and Huffman (1988)). In addition, as in Rotemberg and Woodford (1995), monopolistic competition induces increasing return to scale in the production function. Both of these mechanisms favor the procyclicality of labor productivity.

Finally, looking at inflation and the nominal interest rate, we see that they both rise in response to a positive investment shock. In this respect, the investment shock has the typical features of a "demand" shock, driving quantities and prices in the same direction. In fact, this is one of the distinguishing characteristics of the investment shock, when compared to wage mark-up and neutral technology shocks.

For example, in figure 6 we see that a positive wage mark-up shock depresses all quantities, as well as labor productivity, but leads to an increase in real wages and marginal costs, as well as in inflation and the nominal interest rate: the typical profile of a "supply" shock. Moreover, the responses in quantities and productivity are all extremely persistent.[11] This persistence is presumably the source of the large contribution of the wage mark-up shock to the low frequency fluctuations in hours highlighted in the previous section.

[11] Recall that the labor supply shock is stationary, although its autocorrelation coefficient is estimated to be 0.98.

As we would expect, also neutral technology shocks resemble "supply" shocks. As illustrated in figure 5, output, consumption, investment and wages rise. On the other hand, real marginal costs and inflation fall because neutral technological progress reduces the cost of production. The fact that this disturbance generates comovement on impact between output and consumption is the main reason why its contribution to the volatility of these variables is non-negligible. At the same time, however, hours fall significantly in response to a neutral technology shock, a result consistent with most of the recent SVAR and DSGE literature (see, for instance, Basu, Fernald, and Kimball (2007), Gali (1999), Francis and Ramey (2006), Gambetti (2005), Canova, Lopez-Salido, and Michelacci (2006), Fernald (2007), Gali and Rabanal (2004) and Smets and Wouters (2007)).[12] This negative comovement on impact between output and hours might explain why neutral technology shocks do not have a dominant role for fluctuations in our model.

5. Inspecting the Mechanism: How Investment Shocks Become Important

In a standard neoclassical model (e.g. Kydland and Prescott (1982)), neutral technology shocks are the most natural source of fluctuations, since they can easily produce comovement of output, consumption, investment, hours and labor productivity. In fact, in these models, investment shocks are unlikely candidates to generate business cycles: a positive shock to the marginal efficiency of investment increases the rate of return on capital which, in turn, induces an increase in the opportunity cost of leisure, stimulating labor supply and depressing consumption (Barro and King (1984)). Since capital is fixed in the short run, the labor demand schedule remains unchanged and real wages must decline in equilibrium. Finally, given the constant return to scale, output increases less than labor, inducing a fall in labor productivity (Greenwood, Hercowitz, and Huffman (1988)). These are not the main characteristics of business cycles and it is therefore unlikely that any estimation procedure applied to a neoclassical model puts weight on this shock as an important source of macroeconomic fluctuations.

In our model, on the contrary, investment shocks are the single most important source of volatility in output and hours, explaining between 50 and 60 percent of their variance at business cycle frequencies, as shown in table 5. The main difference from the standard neoclassical model is that our economy features a number of nominal and real frictions, namely

[12] An exception is Christiano, Eichenbaum, and Vigfusson (2004).

consumption habit formation, investment adjustment costs, variable capital utilization and monopolistic competition in products and labor markets (with price and wage stickiness). Each of these frictions play a role in eliminating (or just ameliorating) the problems related to the propagation of the investment shocks highlighted in Barro and King (1984) and Greenwood, Hercowitz, and Huffman (1988), and summarized above.

For instance, habit formation breaks the separability over time of the utility function, violating one of the key assumptions behind Barro and King's (1984) original result. Intuitively, habit formation reduces the extent to which consumption declines in response to a positive investment shock, limiting the negative comovement between consumption and investment. Investment adjustment costs play a very similar role, by preventing investment from rising too rapidly on impact. On the other hand, when the efficiency of investment increases, the return on capital rises and it is optimal to utilize capital more intensively. Hence, utilization rises and so does labor demand because production inputs are complements. As emphasized by Greenwood, Hercowitz, and Krusell (2000), adjustment costs and variable utilization constitute a powerful mechanism that, for instance, can generate a positive response of labor productivity and consumption to an investment shock. Yet, even in the Greenwood, Hercowitz, and Krusell (2000) framework, investment shocks can at most account for one third of output fluctuations.

In our model, however, the presence of monopolistic competition with sticky wages and prices drives an additional endogenous wedge between the marginal rate of substitution between consumption and leisure, and the marginal product of labor. For instance, in response to an investment shock and the consequent rise in the rate of return on capital, real marginal costs increase, or equivalently the equilibrium mark-up in product markets drops, which amplifies the positive shift in labor demand. This counteracts the decline in real wages (which, in fact, are procyclical in our model) and the negative comovement between consumption and labor. In this respect, the endogenous price mark-up plays a similar role to utilization, since it acts as an shifter of labor demand. Similarly, the endogenous wage mark-up act as a shifter of the labor supply.

In the rest of this section, we investigate the quantitative role of these frictions in turning the investment shocks into the foremost source of fluctuations. Hence, we study the variance decomposition of several restricted versions of the baseline model, in which we shut down one category of frictions at-a-time. The groups of frictions that we consider are the following.

First, we estimate a model with no habit in consumption ($h = 0$). The second restriction we impose eliminates endogenous utilization and investment adjustment costs ($1/\chi = 0.0001$ and $S'' = 0$). Third and fourth are models with no wage and price stickiness, and no monopolistic competition in the corresponding markets ($\xi_w = 0.01$, $\iota_w = 0$, $\lambda_w = 1.01$ and $\xi_p = 0.01$, $\iota_p = 0$, $\lambda_p = 1.01$ respectively). Finally, we look at the standard neoclassical model, obtained by simultaneously shutting down all frictions present in the baseline model.

The results of this exercise are reported in table 6. The table focuses on the contributions of investment shocks to the volatility of output and hours at business cycle frequencies, since this is where the importance of investment shocks is most evident. As expected, removing any of these frictions reduces the role of investment shocks in fluctuations. In terms of relative contributions, endogenous utilization and adjustment costs have the most significant marginal impact. Once we shut down these frictions, the contribution of investment shocks to fluctuations in both hours and output drops by more than half. Wage and price rigidities come next. Their exclusion reduces the contribution to output by slightly less than half and to hours by 20 to 30 percent.[13] The friction that plays the smallest role at the margin is time non-separability. Finally, as we would expect, the role of the investment shock completely disappears when all of the frictions are eliminated from the model.

It is important to point out that the inclusion of each of these frictions improves dramatically the overall empirical performance of the model. Table 7 makes this point very clearly, by reporting the marginal data density[14] for the various restricted versions of the model that we have estimated. The fit deteriorates substantially when the model is estimated without some or all of these frictions.

We conclude this section with a note of caution, i.e. by stressing once again that the investment shock alone does not generate the strong comovement of consumption and output observed in the data. While obtaining this comovement is technically possible in our model, our estimates instead imply that consumption dips on impact, although only slightly, and is virtually flat for about one year, while hours and all other quantities boom. The impulse responses of figure 5 make clear that the important source of comovement between

[13] When price and wage rigidities are shut down jointly, the contribution of investment shocks drops even more. This suggests that the effect of endogenous mark-ups is comparable, if not more important than the effect of variable capital utilization and adjustment costs.

[14] The marginal data density (or marginal likelihood) is the expected value of the likelihood function with respect to the prior density and is the appropriate way of comparing models from a Bayesian perspective (see, for instance, Gelman, Carlin, Stern, and Rubin (1995)).

output and consumption is the neutral technology shock, as in the RBC literature. In this respect, the neutral technology and the investment shocks play a complementary role in our model, with the former contributing a significant share of the comovement between output and consumption, and the latter mainly responsible for generating the overall volatility and comovement between output, investment and hours.

Another aspect of this complementarity is that the two shocks can be fairly neatly characterized as a demand and a supply shock, in the sense of generating positive and negative comovement between prices and quantities, as discussed in section 4.2. In this respect, it is interesting that, between the two, the supply shock accounts for a larger share of the variances of wages and inflation. At the same time, the demand shock accounts for almost half of the movements in nominal interest rates. This pattern is consistent with a monetary policy that systematically offsets the inflationary effects of the positive demand shocks it faces by increasing nominal interest rates, but that at the same time remains more "passive" in the face of supply shocks. This behavior is broadly in line with the textbook prescription for optimal monetary policy: lean aggressively against demand shocks, but thread more cautiously in the face of supply shocks, so as to balance the implied trade-off between inflation and real activity. The extent to which this prescription is consistent with welfare maximization from the perspective of the model is an open question for future research.

6. Robustness Analysis

In this section we demonstrate the robustness of our result to a number of alternative specifications of the model. The results of these robustness checks are presented in table 8, which, to save space, only reports the share of the variance of output and hours explained by the investment shock at business cycle frequencies.

6.1. $\alpha = 0.3$ and $\nu = 1$.

Our baseline estimates of the share of capital income (α) and the Frisch elasticity of labor supply ($1/\nu$) differ from the standard values used in the RBC literature. To verify that our estimates of α and ν do not play an important role for the results, we re-estimate the model calibrating $\alpha = 0.3$ and $\nu = 1$, which are more typical values. Table 8 reports the results of this experiment: the investment shocks still explains most of the variation of hours and output at business cycle frequencies.

6.2. **No ARMA shocks.** Following Smets and Wouters (2007), in the baseline model we have assumed that wage and price mark-up shocks follow ARMA(1,1) processes. While the ARMA assumption improves the fit of the model, we want to make sure that our main results do not depend on this assumption. Therefore, we re-estimate the model under the assumption that mark-up shocks follow simpler AR(1) processes instead (Del Negro, Schorfheide, Smets, and Wouters (2007) and Justiniano and Primiceri (2007)). As table 8 makes clear, this modification does not undermine our main results.

6.3. **Output growth in the policy rule.** In our baseline model, the monetary authorities set short term nominal interest rates as a function of inflation and the output gap, defined as the deviation of output from its flexible price level. Since the literature has not reached an agreement on the right measure of real activity that should be included in the policy rule, we re-estimate the model specifying the Taylor rule in terms of output growth, as opposed to the output gap. Table 8 shows that this change is not important for our main result.

6.4. **Smets and Wouters' model.** Another way in which we assess the robustness of our conclusions is by estimating the model of Smets and Wouters (2007), which in an important benchmark. Our model is similar to Smets and Wouters (2007), but there are also a few small differences between the two models: external (SW) versus internal (us) habit formation; deterministic (SW) versus stochastic (us) trend in neutral technology; non-separable (SW) versus separable (us) utility function in consumption and leisure; slightly different priors. Since it would be reassuring to know that these details of the models do not affect the main conclusions, we have estimated exactly the Smets and Wouters (2007) model with their priors on our dataset. Once again, table 8 demonstrates that our results are robust to these changes. Moreover, we notice that this model generates a positive comovement between consumption and investment in response to an investment shock. Closer inspection of the model reveals that this is due to the non-separability between consumption and leisure in the utility function.

6.5. **Maximum Likelihood.** In our baseline exercise, we follow the recent literature on Bayesian estimation of DSGE models and use the prior information reported in table 1. To verify that our priors do not drive our main results, we re-estimate the model by maximum likelihood. Maximizing the likelihood is numerically much more challenging than maximizing the posterior. The use of weakly informative priors, in fact, ameliorates problems related to flatness of the likelihood function and multiple local modes. Nevertheless, we were able to compute the maximum likelihood estimates.[15] As illustrated in table 8, these estimates provide a similar picture of the results: the investment shock still drives most of the business cycle fluctuations in output and hours.

6.6. **Stochastic trend for the investment shock.** In this robustness check, we re-estimate the model allowing for a stochastic trend in the investment shock. This is motivated by the fact that, as long as the investment adjustment costs depend on the consumption value of investment, in our model the inverse of the investment shock can be interpreted as the relative price of investment to consumption goods. Since the relative price of investment has a strong negative trend in the data, it might be important to allow for a positive stochastic trend in the investment shock (whose growth rate can be calibrated using the data on the relative price). In order to estimate this model, we also need to modify our dataset and use the consumption deflator to deflate all nominal variables as well as a price index (see Fisher (2006)). The estimation of this model produces a variance decomposition reported in the last column of table 8. Clearly, all of these modifications are irrelevant for the main result.

7. Concluding Remarks

[To be added]

Appendix A. The Data

Our dataset spans a sample from 1954QIII to 2004QIV. All data are extracted from the Haver Analytics database (series mnemonics in parenthesis). Following Del Negro, Schorfheide, Smets, and Wouters (2007), we construct real GDP by diving the nominal series (GDP) by population (LF and LH) and the GDP Deflator (JGDP). Real series for consumption and investment are obtained in the same manner, although consumption corresponds only to personal consumption expenditures of non-durables (CN) and services (CS), while investment is the sum of personal consumption expenditures of durables (CD) and gross private domestic investment (I). Real wages correspond to nominal compensation per hour in the non-farm business sector (LXNFC), divided by the GDP deflator. We measure the labor

[15] To be precise, in order to maximize the likelihood we need to calibrate $\varkappa$, because the likelihood is not very informative about this parameter and this creates convergence problems in the maximization routine. Therefore, we have calibrated $\varkappa = 5$, which is our prior mean. Notice that this value of $\varkappa$ implies a low elasticity of capital utilization which, if anything, makes the propagation of investment shocks more challenging.

input by the log of hours of all persons in the non-farm business sector (HNFBN), divided by population. The quarterly log difference in the GDP deflator is our measure of inflation, while for nominal interest rates we use the effective Federal Funds rate. We do not demean or detrend any series.

Appendix B. Normalization of the Shocks

As in Smets and Wouters (2007), we re-normalize some of the exogenous shocks by dividing them by a constant term. For instance, one of our log-linearized equilibrium conditions is the following Phillips curve:

$$\hat{\pi}_t = \frac{\beta}{1+\beta\iota_p} E_t \hat{\pi}_{t+1} + \frac{1}{1+\beta\iota_p}\hat{\pi}_{t-1} + \kappa \hat{s}_t + \kappa \hat{\lambda}_{p,t},$$

where $\kappa \equiv \frac{(1-\beta\xi_p)(1-\xi_p)}{(1+\iota_p\beta)\xi_p}$, s_t is the model-implied real marginal cost and the "hat" denotes log deviations from the non-stochastic steady state. The normalization consists of defining a new exogenous variable, $\hat{\lambda}^*_{p,t} \equiv \kappa\hat{\lambda}_{p,t}$, and estimating the standard deviation of the innovation to $\hat{\lambda}^*_{p,t}$ instead of $\hat{\lambda}_{p,t}$. We do the same for the wage mark-up and the intertemporal preference shock, for which we use the following normalizations:

$$\hat{\lambda}^*_{w,t} = \left(\frac{(1-\beta\xi_w)(1-\xi_w)}{\left(1+\nu\frac{\lambda_w}{\lambda_w-1}\right)(1+\beta)\xi_w}\right)\hat{\lambda}_{w,t}$$

$$\hat{b}^*_t = \left(\frac{(1-\rho_b)(e^\gamma - h\beta\rho_b)(e^\gamma - h)}{e^\gamma h + e^{2\gamma} + \beta h^2}\right)\hat{b}_t$$

These normalizations are chosen in such a way that these shocks enter the wage and consumption equations (respectively) with a unity coefficient. In this way it is easier to choose a reasonable prior for their standard deviation. Moreover, the normalization is a practical way to impose correlated priors across coefficients, which is desirable in some cases. For instance, imposing a prior on the standard deviation of the innovation to $\hat{\lambda}^*_{p,t}$ corresponds to imposing prior that allow for correlation between κ and the standard deviation of the innovations to $\hat{\lambda}_{p,t}$. Often, these normalizations improve the convergence properties of the MCMC algorithm.

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Table 1: Prior densities and posterior estimates for baseline model with all frictions

		Prior			Posterior /2		
Coefficient	Description	Prior Density /1	Mean	Std	Median	Std	[5 , 95]
α	Capital Share	N	0.30	0.05	0.17	0.006	[0.16 0.18]
ι_p	Price indexation	B	0.50	0.15	0.24	0.073	[0.14 , 0.39]
ι_w	Wage indexation	B	0.50	0.15	0.11	0.029	[0.06 , 0.16]
γ	SS technology growth rate	N	0.50	0.03	0.48	0.023	[0.44 , 0.52]
h	Consumption habit	B	0.50	0.10	0.79	0.023	[0.76 , 0.83]
λ_p	SS mark-up goods prices	N	0.15	0.05	0.25	0.032	[0.19 , 0.30]
λ_w	SS mark-up wages	N	0.15	0.05	0.15	0.033	[0.07 , 0.19]
$logL^{ss}$	SS leisure	N	396.83	0.50	397.16	0.480	[396.4 , 398.0]
$100(\pi-1)$	SS quarterly inflation	N	0.50	0.10	0.71	0.078	[0.56 , 0.82]
$100(\beta^{-1}-1)$	Discount factor	G	0.25	0.10	0.14	0.045	[0.07 0.22]
ν	Inverse Frisch elasticity	G	2.00	0.75	3.59	0.674	[2.63 , 4.84]
ξ_p	Calvo prices	B	0.66	0.10	0.84	0.016	[0.82 , 0.87]
ξ_w	Calvo wages	B	0.66	0.10	0.71	0.019	[0.68 , 0.74]
χ	Elasticity capital utilization costs	G	5.00	1.00	5.80	1.001	[4.38 , 7.58]
S''	Investment adjustment costs	G	4.00	1.00	2.95	0.301	[2.43 , 3.39]
Φ_p	Taylor rule inflation	N	1.70	0.30	1.97	0.144	[1.71 , 2.20]
Φ_y	Taylor rule output	N	0.13	0.05	0.05	0.012	[0.03 , 0.07]
Φ_{dy}	Taylor rule output growth	N	0.13	0.05	0.23	0.016	[0.21 0.26]
ρ_R	Taylor rule smoothing	B	0.60	0.20	0.81	0.016	[0.79 0.84]

(Continued on the next page)

Table 1: Prior densities and posterior estimates for baseline model with all frictions

Coefficient	Description	Prior Density [/1]	Prior Mean	Prior Std	Posterior [/2] Median	Posterior Std	[5 , 95]	
ρ_{mp}	Monetary Policy	B	0.40	0.20	0.16	0.048	[0.07	0.22]
ρ_z	Neutral Technology growth	B	0.60	0.20	0.23	0.043	[0.15	0.30]
ρ_g	Government spending	B	0.60	0.20	0.99	0.001	[0.99	0.99]
ρ_μ	Investment	B	0.60	0.20	0.73	0.031	[0.68	0.78]
ρ_p	Price mark-up	B	0.60	0.20	0.94	0.017	[0.91	0.96]
ρ_w	Wage mark-up	B	0.60	0.20	0.98	0.003	[0.98	0.99]
ρ_b	Intertemporal preference	B	0.60	0.20	0.65	0.027	[0.60	0.68]
θ_p	Price mark-up MA	B	0.50	0.20	0.78	0.010	[0.76	0.79]
θ_w	Wage mark-up MA	B	0.50	0.20	0.95	0.002	[0.94	0.95]
σ_{mp}	Monetary policy	I	0.10	1.00	0.22	0.012	[0.21	0.25]
σ_z	Neutral Technology growth	I	0.50	1.00	0.89	0.049	[0.81	0.98]
σ_g	Government spending	I	0.50	1.00	0.35	0.017	[0.32	0.38]
σ_μ	Investment	I	0.50	1.00	6.01	0.505	[5.02	6.79]
σ_p	Price mark-up	I	0.10	1.00	0.14	0.002	[0.14	0.15]
σ_w	Wage mark-up	I	0.10	1.00	0.24	0.003	[0.23	0.24]
σ_b	Intertemporal preference	I	0.10	1.00	0.04	0.001	[0.04	0.04]
(log) Likelihood at median						-1094.7		

Calibrated coefficients: depreciation rate (δ) is 0.025, g implies a SS government share of 0.22

Relative to the text, the standard deviations of the innovations are scaled by 100 for the estimation, which is reflected in the prior and posterior estimates.

/1 N stands for Normal, B Beta, G Gamma and I Inverted-Gamma1 distribution

/2 Median and posterior percentiles from 2 chains of 120,000 draws generated using a Random walk Metropolis algorithm, where we discard the initial 20,000 and retain one in every 20 subsequent draws. Additional longer chains produced almost identical posterior moments.

Table 2: Prior variance decomposition for observable variables in the baseline model

Medians and [5,95] prior percentiles

Series \ Shock	**Policy**	**Neutral**	**Government**	**Investment**	**Price mark-up**	**Wage mark-up**	**Preference**
Output growth	0.01	0.26	0.23	0.00	0.00	0.01	0.08
	[0.00,0.33]	[0.02,0.88]	[0.02,0.85]	[0.00,0.04]	[0.00,0.14]	[0.00,0.39]	[0.00,0.74]
Consumption growth	0.01	0.31	0.00	0.00	0.00	0.00	0.42
	[0.00,0.34]	[0.01,0.93]	[0.00,0.11]	[0.00,0.03]	[0.00,0.09]	[0.00,0.27]	[0.02,0.98]
Investment growth	0.01	0.38	0.00	0.03	0.00	0.01	0.04
	[0.00,0.45]	[0.01,0.95]	[0.00,0.13]	[0.00,0.43]	[0.00,0.25]	[0.00,0.69]	[0.00,0.93]
Hours	0.02	0.17	0.07	0.01	0.00	0.04	0.05
	[0.00,0.54]	[0.00,0.90]	[0.00,0.68]	[0.00,0.13]	[0.00,0.29]	[0.00,0.92]	[0.00,0.81]
Wage growth	0.00	0.73	0.00	0.00	0.04	0.09	0.00
	[0.00,0.03]	[0.10,0.99]	[0.00,0.03]	[0.00,0.01]	[0.00,0.50]	[0.01,0.71]	[0.00,0.17]
Inflation	0.01	0.11	0.01	0.00	0.08	0.08	0.03
	[0.00,0.66]	[0.00,0.86]	[0.00,0.19]	[0.00,0.08]	[0.00,0.79]	[0.00,0.95]	[0.00,0.81]
Interest Rates	0.02	0.15	0.02	0.00	0.02	0.03	0.11
	[0.00,0.43]	[0.00,0.92]	[0.00,0.34]	[0.00,0.14]	[0.00,0.50]	[0.00,0.88]	[0.00,0.94]

Since reporting median shares, these need not add up to one, although mean shares do.

Obtained by generating random draws from the prior distributions of the parameters given in table 1.

Table 3: Standard deviations and relative standard deviations in the data and in the baseline model with all frictions /1

	Standard deviation			Relative standard deviation /2		
		Baseline Model			Baseline Model	
Series	Data	Median	[5 , 95]	Data	Median	[5 , 95]
Output growth	0.94	1.14	[1.00 , 1.31]	1.00	1.00	
Consumption growth	0.51	0.72	[0.62 , 0.82]	0.54	0.63	[0.53 , 0.74]
Investment growth	3.59	4.59	[3.95 , 5.36]	3.83	4.03	[3.61 , 4.50]
Hours	4.11	4.47	[3.09 , 6.75]	4.39	3.91	[2.79 , 5.81]
Wage growth	0.55	0.66	[0.59 , 0.75]	0.59	0.58	[0.50 , 0.67]
Inflation	0.60	0.49	[0.39 , 0.63]	0.64	0.43	[0.34 , 0.56]
Interest Rates	0.84	0.66	[0.52 , 0.83]	0.90	0.58	[0.45 , 0.74]

/1 For each parameter draw, we generate 1000 samples of the observable series implied by the model with same length as our dataset (202 observations) after discarding 50 initial observations. For the relative standard deviations, for each replication and parameter draw we take the ratio of the standard deviation of each series to that of output. Table reports median and 5th and 95th percentile together with the corresponding moments in the data.

2/ Standard deviation relative to the standard deviation of output growth

Table 4: Posterior variance decomposition for observable variables in the baseline model

Medians and [5,95] posterior percentiles

Series \ Shock	**Policy**	**Neutral**	**Government**	**Investment**	**Price mark-up**	**Wage mark-up**	**Preference**
Output growth	0.04	0.20	0.07	0.51	0.04	0.05	0.09
	[0.03, 0.06]	[0.15, 0.25]	[0.06, 0.08]	[0.45, 0.57]	[0.03, 0.05]	[0.03, 0.07]	[0.07, 0.11]
Consumption growth	0.02	0.26	0.02	0.07	0.01	0.09	0.53
	[0.01, 0.03]	[0.21, 0.32]	[0.02, 0.03]	[0.04, 0.11]	[0.00, 0.01]	[0.06, 0.13]	[0.46, 0.60]
Investment growth	0.03	0.05	0.00	0.87	0.03	0.01	0.01
	[0.02, 0.04]	[0.04, 0.07]	[0.00, 0.00]	[0.84, 0.89]	[0.02, 0.04]	[0.01, 0.01]	[0.01, 0.02]
Hours	0.02	0.03	0.02	0.20	0.05	0.65	0.02
	[0.02, 0.04]	[0.02, 0.04]	[0.01, 0.03]	[0.12, 0.30]	[0.03, 0.07]	[0.52, 0.77]	[0.01, 0.03]
Wage growth	0.00	0.29	0.00	0.03	0.22	0.46	0.00
	[0.00, 0.00]	[0.23, 0.34]	[0.00, 0.00]	[0.02, 0.04]	[0.18, 0.27]	[0.42, 0.50]	[0.00, 0.00]
Inflation	0.03	0.07	0.00	0.06	0.24	0.56	0.02
	[0.02, 0.06]	[0.05, 0.11]	[0.00, 0.00]	[0.03, 0.11]	[0.17, 0.32]	[0.44, 0.68]	[0.01, 0.03]
Interest Rates	0.10	0.05	0.01	0.45	0.02	0.24	0.11
	[0.08, 0.14]	[0.04, 0.08]	[0.01, 0.01]	[0.34, 0.57]	[0.02, 0.04]	[0.13, 0.37]	[0.08, 0.15]

Since reporting median shares, these need not add up to one, although mean shares do.

Table 5: Variance decomposition at business cycle frequencies[/1] in the baseline model with all frictions

Medians and [5,95] posterior percentiles

Series \ Shock	**Policy**	**Neutral**	**Government**	**Investment**	**Price mark-up**	**Wage mark-up**	**Preference**
Output	0.05	0.24	0.02	0.53	0.05	0.04	0.07
	[0.04, 0.07]	[0.18, 0.30]	[0.01, 0.02]	[0.45, 0.61]	[0.03, 0.07]	[0.03, 0.06]	[0.05, 0.09]
Consumption	0.02	0.27	0.02	0.08	0.01	0.08	0.51
	[0.01, 0.03]	[0.21, 0.33]	[0.02, 0.03]	[0.05, 0.14]	[0.00, 0.01]	[0.05, 0.12]	[0.42, 0.59]
Investment	0.03	0.06	0.00	0.85	0.04	0.01	0.01
	[0.02, 0.04]	[0.04, 0.09]	[0.00, 0.00]	[0.81, 0.89]	[0.02, 0.05]	[0.01, 0.01]	[0.01, 0.02]
Hours	0.06	0.10	0.02	0.61	0.06	0.06	0.08
	[0.05, 0.09]	[0.08, 0.13]	[0.02, 0.03]	[0.54, 0.67]	[0.04, 0.08]	[0.03, 0.08]	[0.06, 0.11]
Wages	0.00	0.39	0.00	0.04	0.31	0.25	0.00
	[0.00, 0.01]	[0.30, 0.47]	[0.00, 0.00]	[0.02, 0.07]	[0.24, 0.38]	[0.21, 0.31]	[0.00, 0.01]
Inflation	0.03	0.14	0.00	0.07	0.40	0.31	0.02
	[0.02, 0.05]	[0.10, 0.19]	[0.00, 0.00]	[0.04, 0.13]	[0.32, 0.49]	[0.25, 0.38]	[0.01, 0.03]
Interest Rates	0.18	0.09	0.01	0.48	0.04	0.04	0.15
	[0.14, 0.23]	[0.07, 0.12]	[0.00, 0.01]	[0.41, 0.56]	[0.03, 0.06]	[0.03, 0.06]	[0.11, 0.19]

Since reporting median shares, these need not add up to one, although mean shares do.

/1 Decomposition of the variance corresponding to periodic components with cycles of between 6 and 32 quarters, obtained using the spectrum of the DSGE model and an inverse first difference filter for output, consumption, investment and wages to obtain the levels. The spectral density is computed from the state space representation of the model and 500 bins for frequencies covering that range of periodicities. Results are identical to those that would result from repeatedly simulating the observables, obtaining the levels and then applying a Band-Pass filter. Variance shares for periods of 2 to 32 quarters obtained with the spectrum implied by the DSGE, or by HP filtering the model observables (transformed to levels where appropriate) deliver a very similar decomposition.

Table 6: Variance share for output and hours at business cycle frequencies[/1] explained by investment shocks for alternative specifications without some frictions

Series	No habits /2	No wage rigidities /3	No price rigidities /4	No investment costs & capital utilization /5	All frictions off /6
Output	0.38	0.31	0.30	0.23	0.02
Hours	0.50	0.41	0.50	0.30	0.03

/1 Share of the variance of output (level) and hours, corresponding to periodic components of cycles between 6 and 32 quarters explained by investment shocks alone. Obtained using the spectrum from the state-space representation of the DSGE. See table 4 for further details and the shares for the baseline specification with all frictions. No posterior bands are reported here since the variance decompositions are performed at the mode of each specification. Future versions of the paper will include these bands using MCMC draws.

/2 h calibrated at 0.01

/3 λ_{w}, ξ_{w} and ι_{w} calibrated at 0.01

/4 λ_{p}, ξ_{p} and ι_{p} calibrated at 0.01

/5 S'' calibrated at 0.01, $1/\chi$ calibrated at 0.001

/6 combines the calibration for each of the four specifications above

Table 7: Log-Marginal Data Densities for baseline and alternative specifications without some frictions

Specification	Log Marginal [/1]
Baseline [2/]	-1215.10
No habits	-1316.75
No wage rigidities	-1283.19
No price rigidities	-1433.42
No investment costs and capital utilization	-1298.04
All frictions off	-1521.88

/1 Except for the baseline, the log marginal data density is computed using the Metropolis-Laplace approximation at the posterior mode. In future version of the paper, all marginals will be computed as in the baseline, using the modified harmonic mean and posterior draws. The specification favored by the data attains the highest marginal density.

2/ Parameter estimates shown in Table 1

Full set of parameter estimates for the remaining models is available from the authors upon request

Table 8: Robustness check for the variance share of output and hours at business cycle frequencies [1] explained by investment shocks alone

Series	MLE /2	*η=1* and *α=0.3*	No MA components /3	Taylor rule with output growth /4	Smets and Wouters (AER 07) /5	Two trends /6
Output	0.60	0.66	0.52	0.49	0.56	0.55
Hours	0.64	0.77	0.56	0.54	0.56	0.70

/1 Share of the variance of output (level) and hours, corresponding to periodic components of cycles between 6 and 32 quarters explained by investment shocks alone. Obtained using the spectrum from the state-space representation of the DSGE. See table 4 for further details and the shares for the baseline specification with all frictions. No posterior bands are reported here since the variance decompositions are performed at the mode of each specification. Future versions of the paper will include these bands using MCMC draws, except for the model estimated by maximum likelihood.

/2 Baseline specification estimated by maximum likelihood.

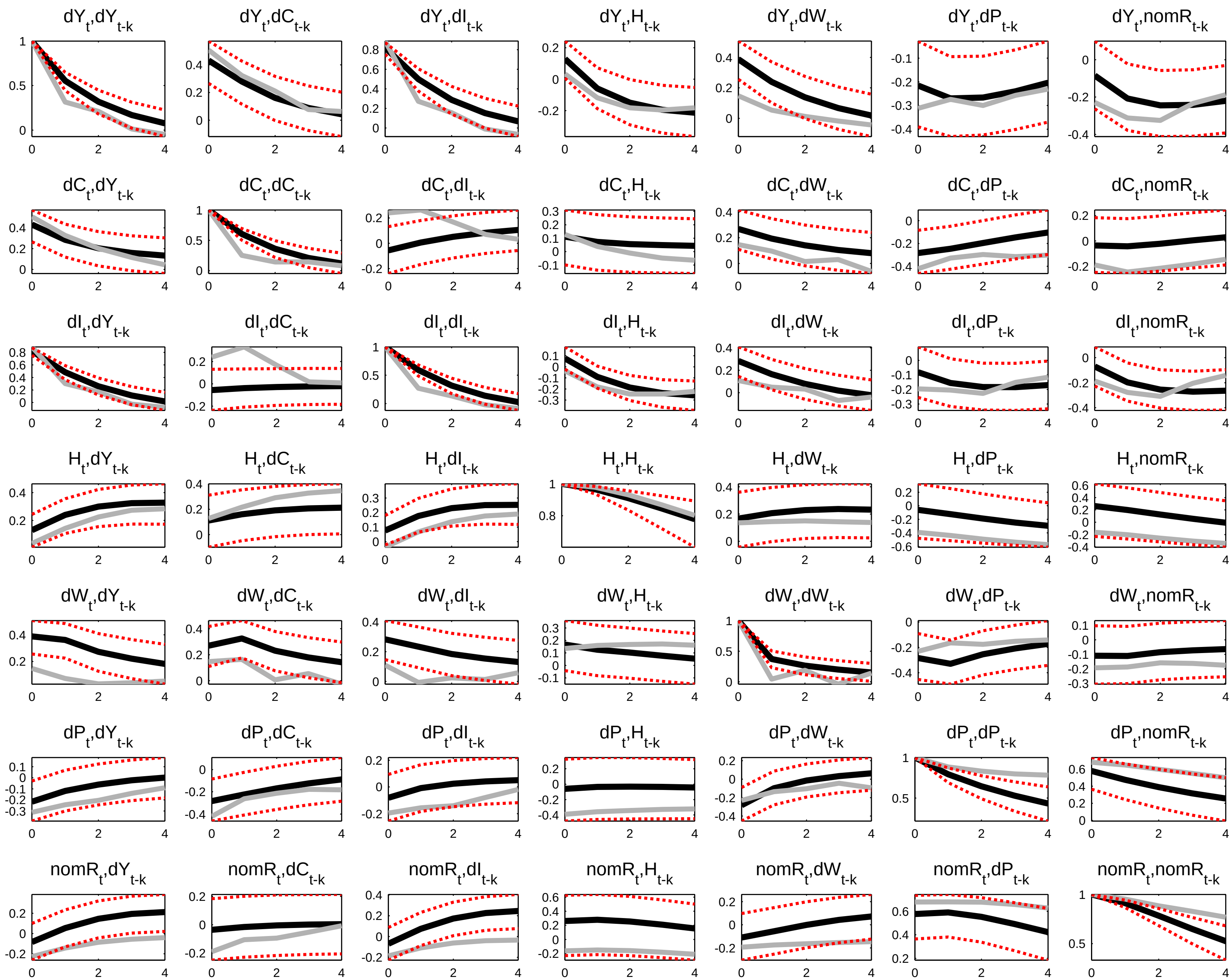
/3 Moving average component for price and wage mark-up shocks calibrated to zero.

/4 Taylor rule responds to observable output growth instead of the output gap.

/5 Smets and Wouters' (AER 2007) model estimated by Bayesian methods with their priors, using our dataset and sample.

/6 Model with two stochastic trends, in neutral technology and investment shocks

Fig 1: Autocorrelation for baseline specification, dsge median (dark), dsge 5-95 (dotted) & data (grey)



legend: dY=output growth, dC=consumption growth, dI=investment growth, H=hours, dW=wages growth, dP=inflation, nomR=nominal interest rate

Figure 2: Actual and counterfactual annualized output growth explained by investment shocks alone

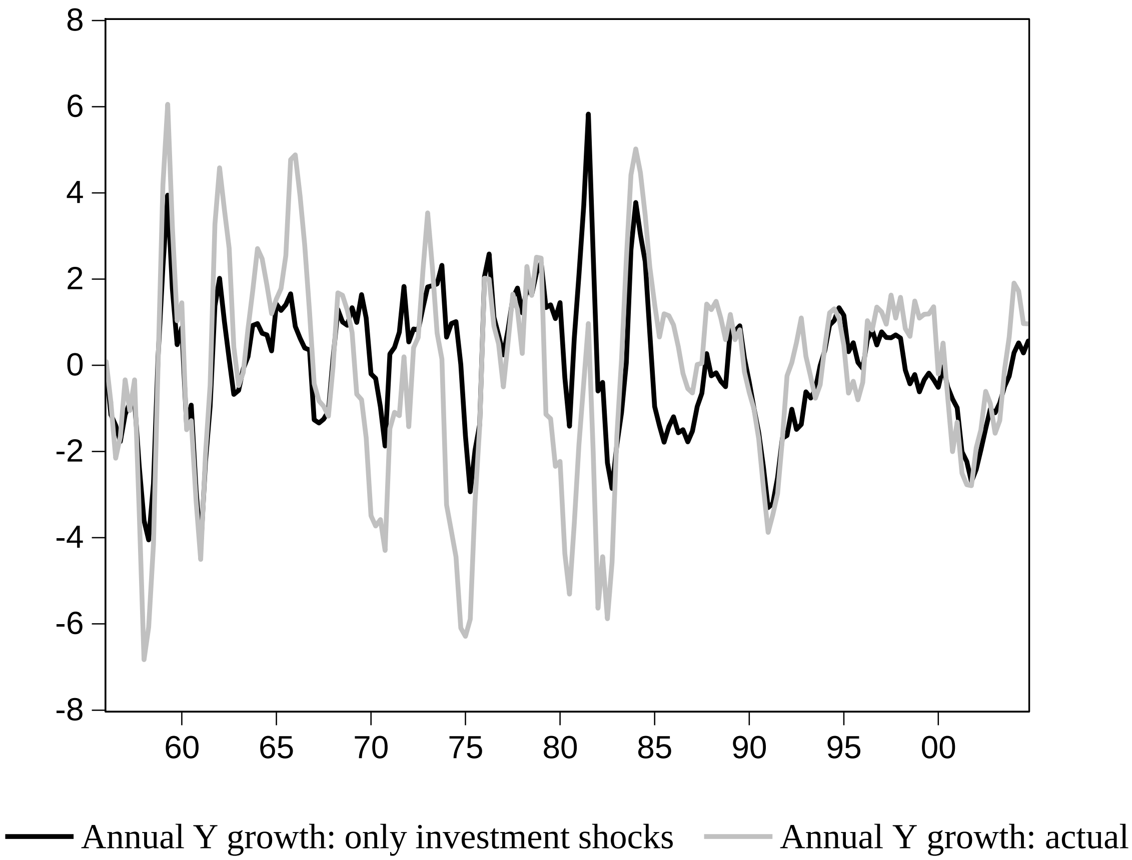
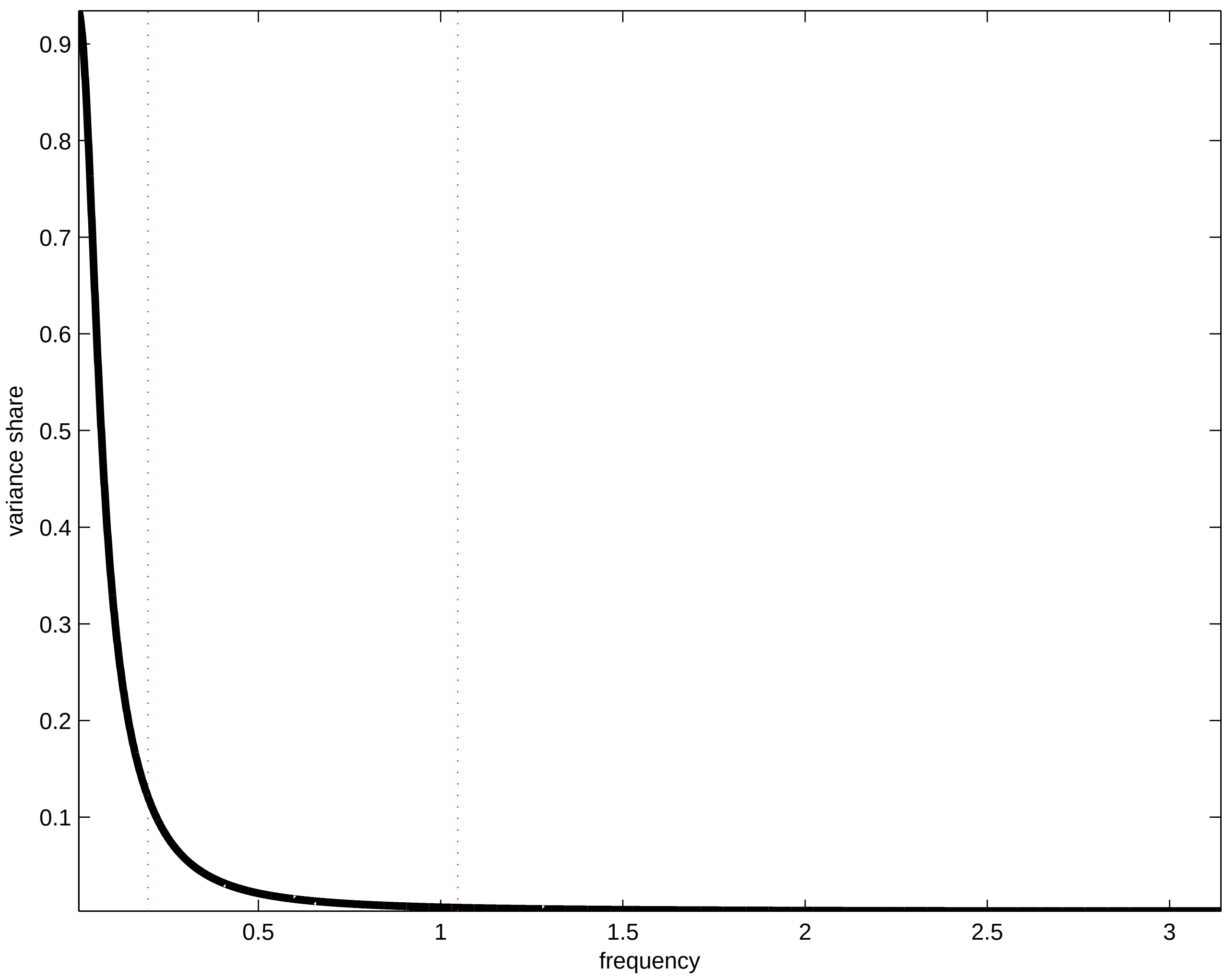


Figure 3: Variance share of Hours explained by
wage mark−up shocks alone at all frequencies



Vertical dashed lines mark the frequency band associated with business cycles of 6 to 32 quarters

Figure 4: investment IRF

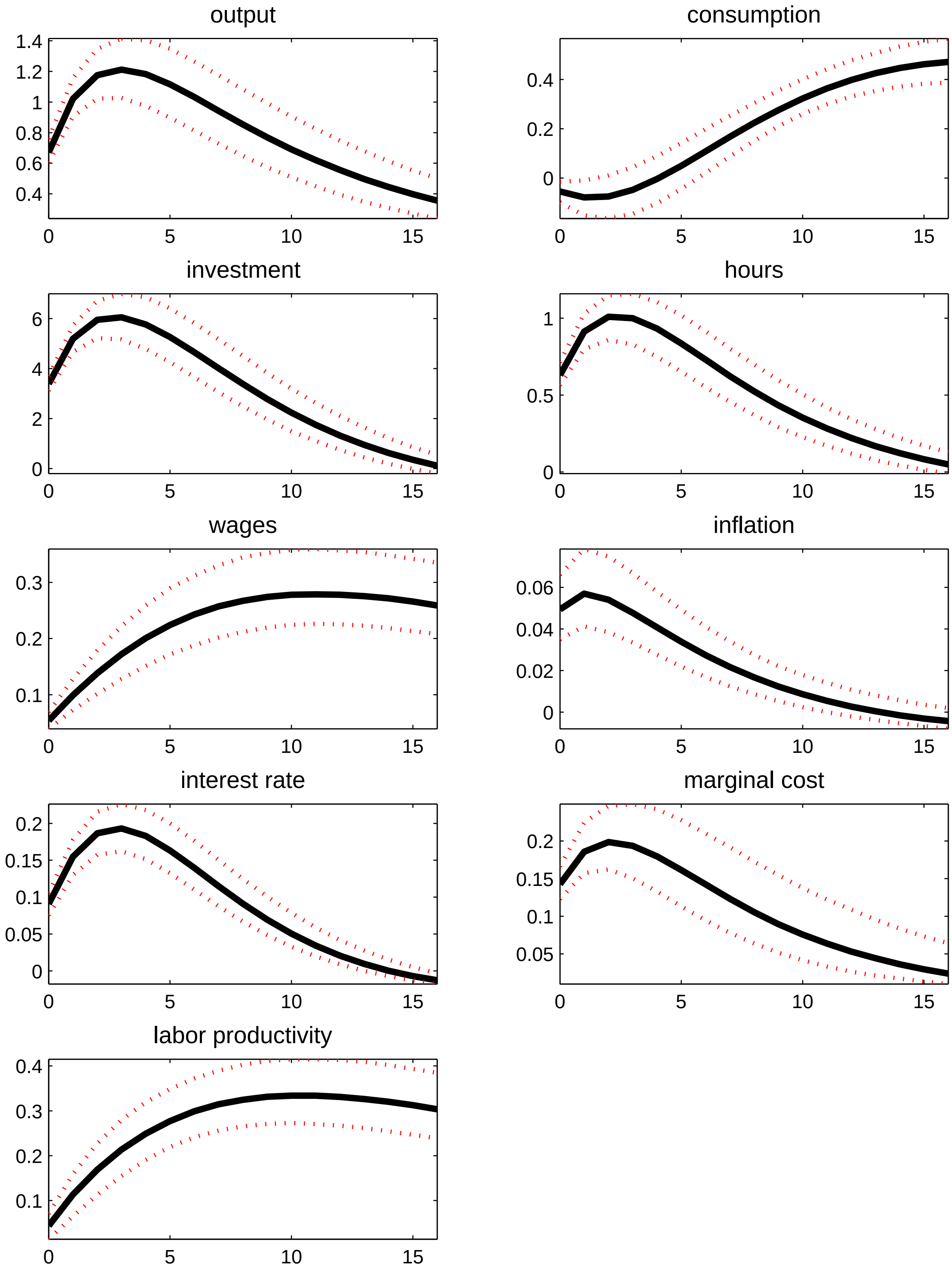


Figure 5: neutral IRF

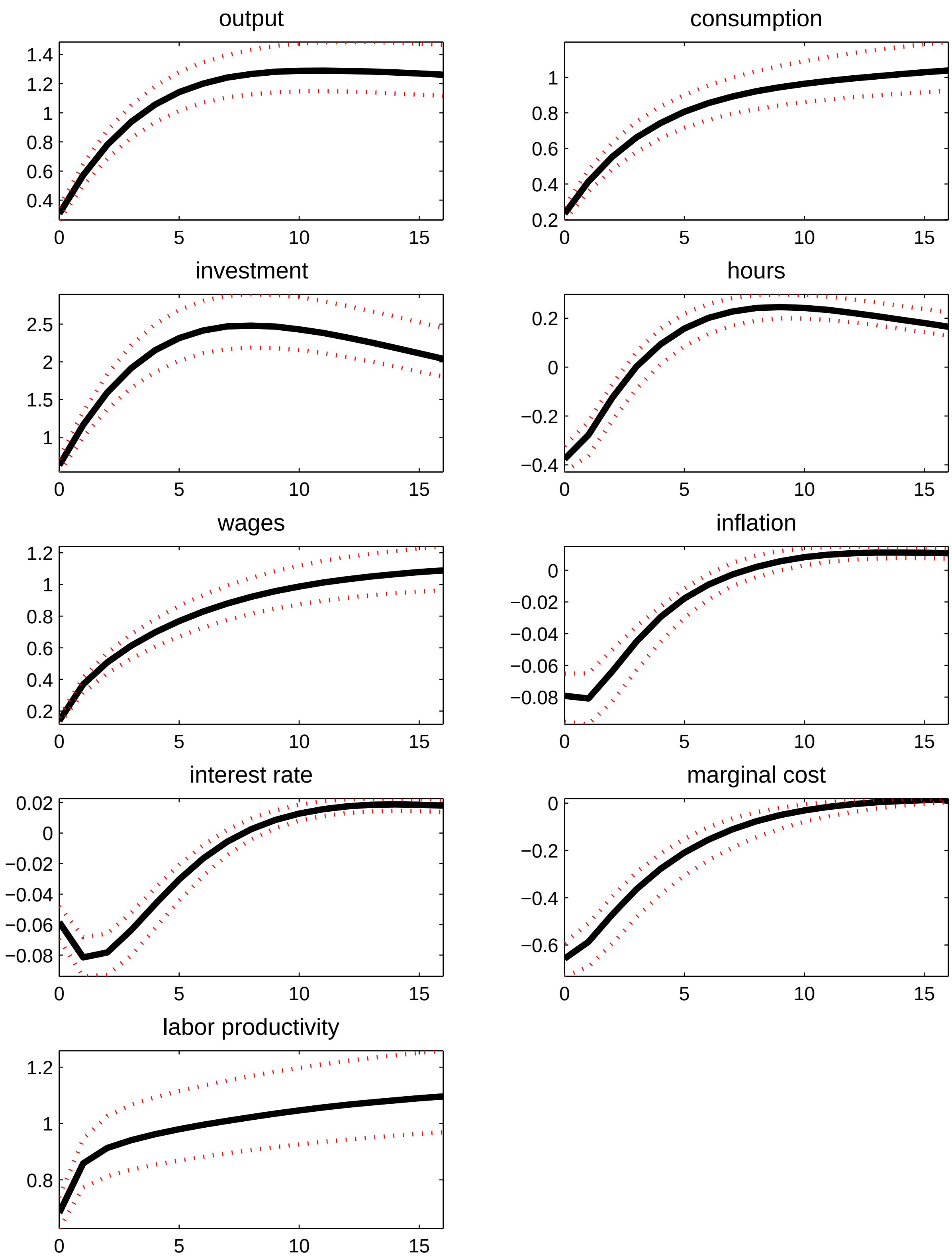


Figure 6: wage mark−up IRF