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Investment shocks and the relative price of investment ☆

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ABSTRACT

We estimate a New-Neoclassical Synthesis business cycle model with two investment shocks. The first, an investment-specific technology shock, affects the transformation of consumption into investment goods and is identified with the relative price of investment. The second shock affects the production of installed capital from investment goods or, more broadly, the transformation of savings into the future capital input. We find that this shock is the most important driver of U.S. business cycle fluctuations in the post-war period and that it is likely to proxy for more fundamental disturbances to the functioning of the financial sector. To corroborate this interpretation, we show that it is closely related to interest rate spreads and that it played a particularly important role in the recession of 2008–2009.

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1. Introduction

Discussion of the sources of business cycles has recently regained center stage in the public and academic debates, following the most severe and protracted recession of the post-war period, which was triggered and magnified by a deep financial crisis. These events are hard to reconcile with the conventional macroeconomic view of the past twenty five years, that business cycles are best understood as efficient responses of a frictionless economy to exogenous movements in total factor productivity. We argue that a more promising view of the driving forces of macroeconomic fluctuations in general, and of the current recession in particular, is one that attributes them largely to investment shocks—disturbances that affect the transformation of current savings into the future capital input.

Greenwood et al. (1988) were the first to suggest that investment shocks could be a viable alternative to neutral technology shocks as sources of business cycles in a general equilibrium environment. The appeal of these disturbances was later enhanced by the work of Greenwood et al. (1997) and Fisher (2006). The former suggested that investment-specific technological progress—a kind of investment disturbance identified with trend reductions in the price of investment relative to consumption—is responsible for the major share of growth in the post-war U.S. The latter showed, using structural VARs,

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that the shock responsible for permanent changes in the relative price of investment accounts for a large part of the fluctuations in output and hours. Both these contributions rely on the observation that, in equilibrium, technological improvements in the production of investment goods should be reflected in their relative price.

In a recent paper (Justiniano et al., 2010, JPT hereafter), we showed that an investment shock that determines the efficiency of newly produced investment goods, as in Greenwood et al. (1988), is the key driver of business cycles in a medium-scale, estimated New-Neoclassical Synthesis model. Our procedure to identify this shock, however, ignored any restriction on its behavior imposed by the observation of the relative price of investment. In fact, our estimates implied an investment disturbance four times as volatile and only weakly correlated with available measures of the relative price of investment (see Justiniano et al., 2008, Section 6). Instead, using one of these measures to identify all investment shocks in an estimated DSGE model similar to ours, Schmitt-Grohe and Uribe (2008) found that their contribution to macroeconomic fluctuations is negligible.

In this paper, we study the relationship between investment shocks and the relative price of investment more closely. We do so in a generalization of the baseline model of JPT, in which the production of consumption, investment and capital goods is explicitly decentralized into separate sectors. The point of this stylized decentralization is to highlight that the process of capital accumulation can be affected by at least two kinds of shocks. On the one hand, investment-specific technology (IST) shocks influence the transformation of consumption into investment goods. On the other hand, shocks to the marginal efficiency of investment (MEI) affect the process by which investment goods are transformed into productive capital.

Our first contribution is to disentangle the role of these two shocks in business cycles. This is feasible because, in the equilibrium of our model, the IST shock is exactly equal to the inverse of the price of investment relative to consumption. When we impose this restriction, by including the relative price of investment among the observables, we find that MEI shocks are the single most important source of macroeconomic fluctuations. These shocks explain between 60 and 85 percent of the variance of output, hours and investment at business cycle frequencies, although they account for little of the volatility of consumption. On the contrary, the contribution of the IST shock is negligible, as in Schmitt-Grohe and Uribe (2008).[1]

The prominent role played by MEI shocks in business cycles leaves open the question of their ultimate origin. The paper's second contribution is to point out that these investment shocks might proxy for more fundamental disturbances to the intermediation ability of the financial system. This interpretation is based on the agency cost model of Bernanke and Gertler (1989) and Carlstrom and Fuerst (1997). Just like their agency cost, in fact, MEI shocks influence the efficiency with which goods can be turned into capital ready for production. To corroborate this interpretation, we show that the sequence of MEI shocks implied by our estimates is highly correlated with credit spreads and that it accounts for most of the fall in output and hours in 2007 and 2008. Encouraged by this evidence, we estimate a version of the model in which data on spreads discipline the behavior of the marginal efficiency of investment. Even with this restriction, MEI shocks continue to account for a large fraction of macroeconomic fluctuations.

One qualification to our results is that the equality between the relative price of investment and the inverse of investment-specific productivity would generally not hold in more realistic versions of our multi-sector model. For example, if the production of investment goods takes place in a non-competitive sector with nominal rigidities, the resulting markup creates an endogenous wedge between the relative price of investment and the inverse of the IST shock, as we show in Appendix A. In fact, the presence of such a wedge is a common phenomenon in non-competitive economies (e.g. Floetotto et al., 2009) and might be important to reconcile our results with those of Fisher (2006).[2]

Overall, our conclusion is that the strategy of identifying all shocks to the capital accumulation process with the relative price of investment is not robust to reasonable generalizations of the simplest two-sector theoretical framework and can therefore deliver misleading results.

The paper proceeds as follows. Section 2 presents a streamlined multi-sector version of the canonical DSGE model for the study of business cycles. Section 3 derives an equivalent one-sector representation that highlights the role of investment shocks in the capital accumulation process. Sections 4 and 5 describe our approach to inference and the main estimation results, with particular emphasis on the variance decomposition. Section 6 elaborates on the economic interpretation of MEI shocks. Section 7 concludes.

2. The model

This section outlines our model of business cycles in the U.S. economy. It is a medium scale DSGE model with a neoclassical growth core, which we augment with several departures from the canonical assumptions on tastes, technology and market structure. All these departures are now quite common in the literature. This model is an ideal framework for the study of business cycles, for two reasons. First, it fits the data well, as demonstrated for example by Del Negro et al. (2007) and Smets and Wouters (2007). Second, it encompasses a number of views on the origins of business cycles that have been proposed in the literature.

[1] In a very recent paper on the sources of the Great Moderation, Liu et al. (2009) also find that IST shocks identified with the relative price of investment account for almost none of the variability of macroeconomic variables, while a shock to depreciation plays a fairly important role.

[2] Guerrieri et al. (2010) present a real two-sector model calibrated to the U.S. input–output structure, in which the equality between the relative price of investment and the inverse of IST does not hold due to differences in the factor intensities of the two sectors.

Relative to JPT's baseline model, here we allow for non-stationary investment-specific technological progress. Moreover, we distinguish explicitly between consumption and investment goods on the one hand and installed capital on the other. These three goods are produced in three different sectors. In particular, a chain of intermediate and final good firms produces the final good, using capital and labor as inputs. The final good can either be consumed by households or used as an input by investment good producers. Investment goods, in turn, are used as inputs for the production of capital. The rest of the model is standard, with households who consume, accumulate capital, and supply labor services, and a government.

The multi-sector decentralization of the capital accumulation process we propose, although extremely streamlined, helps to clarify the distinction between shocks that affect the relative price of investment and shocks that do not. This distinction is crucial, since we want to discipline the inference on the role of investment shocks in business cycles with observations on the relative price of investment. The inclusion of this relative price among the observables in the estimation procedure is the second important difference in this paper with respect to the approach followed in JPT.

2.1. Consumption good producing sector

The final consumption good is produced by a chain of intermediate and final good producers. We start by describing their optimization problems.

2.1.1. Final good producers

At every point in time t, perfectly competitive firms produce the final good Y_t combining a continuum of intermediate goods $\{Y_t(i)\}_i$, $i \in [0,1]$, according to the technology

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

We assume that $\lambda_{p,t}$ 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 $i.i.d.N(0,\sigma_p^2)$. We refer to this as a *price markup* shock, since $\lambda_{p,t}$ is the desired markup of price over marginal cost for intermediate firms. As in Smets and Wouters (2007), the ARMA$(1,1)$ structure of the desired markup helps capture the moving average, high frequency component of inflation.

The final good is purchased at a unit price P_t by households, who use it for consumption, and by the firms operating in the investment sector, who use it as an input in the production of the investment good. Profit maximization and the zero profit condition imply that the price P_t is a CES aggregate of the prices of the intermediate goods, $\{P_t(i)\}_i$

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

and that the demand function for intermediate good i is

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t. \tag{2.1}$$

2.1.2. Intermediate goods producers

Each intermediate good $Y_t(i)$ is produced by a monopolist according to the technology

$$Y_t(i) = \max\left\{ A_t^{1-\alpha} K_t(i)^{\alpha} L_t(i)^{1-\alpha} - A_t \Upsilon_t^{\frac{\alpha}{1-\alpha}} F; 0 \right\}, \tag{2.2}$$

where $K_t(i)$ and $L_t(i)$ denote the amounts of effective capital and labor employed by firm i. A_t represents exogenous labor-augmenting technological progress or, equivalently, a *neutral technology* factor. The level of neutral technology is non-stationary and its growth rate ($z_t \equiv \Delta \log A_t$) follows a stationary AR(1) process

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

with $\varepsilon_{z,t}$ $i.i.d.N(0,\sigma_z^2)$. The variable Υ_t represents instead investment-specific technological progress, whose properties will be detailed below. The composite technological process $A_t \Upsilon_t^{\frac{\alpha}{1-\alpha}}$ multiplies the fixed costs of production, F, to ensure the existence of a balanced growth path. We choose the value of F so that profits are zero in steady state (see Rotemberg and Woodford, 1995 and Christiano et al., 2005).

As in Calvo (1983), every period a fraction ξ_p of intermediate firms cannot optimally choose their price, but reset it according to the indexation rule

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

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$ is gross inflation and π is its steady state. The remaining fraction of firms choose their price, $\tilde{P}_t(i)$, by maximizing the present discounted value of future profits

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

subject to the demand function (2.1) and the production function (2.2). In this objective, λ_{t+s} is the marginal utility of nominal income of the representative household that owns the firm, while W_t and r_t^k are the nominal wage and the rental rate of capital.

2.2. Investment good producing sector

Perfectly competitive firms purchase Y_t^I units of the final good to transform them into investment goods *in efficiency units* (I_t), which they sell to capital producers at a unit price P_{It}. Their objective is to maximize the profit function

$$P_{It} I_t - P_t Y_t^I,$$

subject to the production technology

$$I_t = \Upsilon_t Y_t^I.$$

The slope of this linear function, Υ_t, represents *investment-specific technological* (*IST*) progress, increases in the quantity or quality of investment goods that can be produced from given inputs. IST progress is non-stationary and its growth rate ($\upsilon_t = \Delta \log \Upsilon_t$) evolves exogenously according to the process

$$\upsilon_t = (1 - \rho_\upsilon)\gamma_\upsilon + \rho_\upsilon \upsilon_{t-1} + \varepsilon_{\upsilon,t},$$

with $\varepsilon_{\upsilon,t}$ $i.i.d.N(0, \sigma_\upsilon^2)$.

2.3. Capital good producing sector

Perfectly competitive firms purchase investment goods and transform them into installed capital, which is then sold to households. The technology to produce new capital, i_t, is given by

$$i_t = \mu_t \left(1 - S\left(\frac{I_t}{I_{t-1}} \right) \right) I_t. \tag{2.3}$$

The function S captures the presence of adjustment costs in investment, as in Christiano et al. (2005). We assume that, in steady state, $S = S' = 0$ and $S'' > 0$. The shock μ_t to the *marginal efficiency of investment* (MEI) represents an exogenous disturbance to the process by which investment goods are transformed into installed capital to be used in production. We assume that it follows the stochastic process

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

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

Capital producers maximize the expected discounted value of future profits

$$E_t \sum_{s=0}^{\infty} \beta^s \lambda_{t+s} \left[P_{kt+s} i_{t+s} - P_{It+s} I_{t+s} \right],$$

where P_{kt} denotes the price of installed capital per efficiency unit. Their objective is intertemporal, due to the particular form of adjustment costs postulated in Eq. (2.3), whereby a higher level of investment today reduces adjustment costs tomorrow, everything else equal.

2.4. Households

The economy is populated by a continuum of households, each endowed with a specialized type of labor $j \in [0, 1]$. Household j maximizes the utility function

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

where C_t is consumption, h is the degree of habit formation, $L_t(j)$ denotes the supply of specialized labor and b_t is a shock to the discount factor, which affects both the marginal utility of consumption and the marginal disutility of labor. This *intertemporal preference* shock follows the stochastic process

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

with $\varepsilon_{b,t} \sim i.i.d.N(0,\sigma_b^2)$. Since technological progress is non stationary, we work with log utility to ensure the existence of a balanced growth path. 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.

As a result, the household's budget constraint is

$$P_t C_t + P_{kt} i_t + T_t + B_t \leqslant R_{t-1} B_{t-1} + Q_t(j) + \Pi_t + W_t(j) L_t(j) + r_t^k u_t \bar{K}_{t-1} - P_t \frac{a(u_t)}{\Upsilon_t} \bar{K}_{t-1},$$

where 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 household's j portfolio of 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 installed 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 dollar cost of capital utilization per unit of physical capital is $P_t a(u_t)/\Upsilon_t$. It is scaled by the IST factor to ensure the existence of a balanced growth path. We assume $u_t = 1$ in steady state, $a(1) = 0$ and define $\chi \equiv \frac{a''(1)}{a'(1)}$. The physical capital accumulation equation is

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + i_t,$$

where δ is the depreciation rate.

Each household is a monopolistic supplier of specialized labor, $L_t(j)$, as in Erceg et al. (2000). A large number of competitive "employment agencies" combine this specialized labor into a homogeneous labor input sold to intermediate firms, according to

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

As in the case of the final good, the desired markup of the wage over the household's marginal rate of substitution, $\lambda_{w,t}$, 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 is the wage markup shock. We also refer to it as a *labor supply* shock, since its effect on the household's first order condition for the choice of hours is identical to that of the preference shock analyzed by Hall (1997).

Profit maximization by the perfectly competitive employment agencies implies the labor demand function

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

where $W_t(j)$ is the wage received by the supplier of labor of type j, while the wage paid by intermediate firms for their homogeneous labor input is

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

In terms of wage setting, we also follow Erceg et al. (2000) and assume that every period a fraction ξ_w of households cannot freely set their wage, but sets them according to the indexation rule

$$W_t(j) = W_{t-1}(j)\left(\pi_{t-1} e^{z_{t-1} + \frac{\alpha}{1-\alpha}\upsilon_t}\right)^{\iota_w} \left(\pi\, e^{\gamma_z + \frac{\alpha}{1-\alpha}\gamma_\upsilon}\right)^{1-\iota_w},$$

so as to preserve balance growth in the model. The remaining fraction of households chooses instead an optimal wage by maximizing their utility, subject to the labor demand function.

2.5. Government

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

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

where the *government spending shock* g_t follows the stochastic process

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

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

A monetary policy authority sets the nominal interest rate following a feedback rule of the form

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi}\left(\frac{X_t}{X_t^*}\right)^{\phi_X}\right]^{1-\rho_R}\left[\frac{X_t/X_{t-1}}{X_t^*/X_{t-1}^*}\right]^{\phi_{dX}}\varepsilon_{mp,t},$$

where R is the steady state of the gross nominal interest rate. As in Smets and Wouters (2007), the interest rate responds to deviations of inflation from its steady state, as well as to the level and the growth rate of the GDP gap (X_t/X_t^*).[3] The monetary policy rule is also perturbed by a *monetary policy* shock, $\varepsilon_{mp,t}$, which is $i.i.d.N(0,\sigma_{mp}^2)$.

2.6. Model solution

In this model, consumption, investment, capital, real wages and output fluctuate around a stochastic balanced growth path, since the levels of neutral and investment-specific technology have a unit root. The resulting composite trend is given by $A_t\Upsilon_t^{\frac{\alpha}{1-\alpha}}$, with steady state growth rate

$$\gamma_* = \gamma_z + \frac{\alpha}{1-\alpha}\gamma_\upsilon.$$

Therefore, the solution involves the following steps. First, we rewrite the model in terms of detrended stationary variables. We then compute the non-stochastic steady state of the transformed model, and log-linearly approximate it around this steady state. Finally, we solve the resulting linear system of rational expectation equations.

3. Investment shocks and the relative price of investment

The model we just presented distinguishes between final consumption goods, investment goods and newly installed capital, and therefore produces explicit expressions for their equilibrium prices. For instance, profit maximization by the competitive investment good producers implies that their price (P_{It}) equals marginal cost $(P_t\Upsilon_t^{-1})$. As a result, the price of investment in terms of consumption goods coincides with the inverse of the IST process

$$\frac{P_{It}}{P_t} = \Upsilon_t^{-1}. \tag{3.1}$$

In perfect competition, the benefits of any improvement in the production of investment goods immediately translate into a lower price per efficiency unit.

Thanks to this equilibrium condition, we can derive a one-sector representation of the model. The zero profit condition of capital producers implies

$$P_{kt}i_t = P_t\tilde{I}_t, \tag{3.2}$$

where $\tilde{I}_t \equiv \frac{P_{It}}{P_t}I_t$ is real investment in consumption units. The substitution of Eqs. (3.1), (3.2) and (2.3) into the households' budget constraint and the capital accumulation equation yields a one-sector model comparable to those in Altig et al. (2005), Smets and Wouters (2007) or JPT. This one-sector representation of the model features an accumulation equation for physical capital of the form

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + \mu_t\Upsilon_t(1-S_t)\tilde{I}_t, \tag{3.3}$$

where $S_t \equiv S(I_t/I_{t-1})$ denotes the investment adjustment cost paid at time t.

The accumulation process described by Eq. (3.3) is affected by two disturbances: the IST shock Υ_t and the MEI shock μ_t. This distinction between two investment shocks sets our model apart from those in most existing studies, which either equate the combined shock to the relative price of investment, thus implicitly ignoring μ_t (e.g. Schmitt-Grohe and Uribe, 2008; Altig et al., 2005), or treat the two disturbances as a unique unobservable shock (e.g. Smets and Wouters, 2007, JPT).

In this paper, we can separately identify the two disturbances because we use observations on the relative price of investment to pin down the evolution of IST progress, as suggested by Eq. (3.1) (see also Christiano et al., 2007). The discipline imposed by this approach on the properties of the IST shock implies that its contribution tofluctuations is negligible, as we will see in Section 5. On the contrary, the MEI shock plays a key role in business cycles. The estimation procedure by which we achieve this identification is described in the next section.

[3] The GDP gap is the difference between actual GDP $(C_t + I_t + G_t)$ and its efficient level (Woodford, 2003).

4. Bayesian inference and the observable variables

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. The rest of this section discusses the data used to evaluate the likelihood function and the specification of the priors.

4.1. Data

We estimate the model using

$$\left[\Delta \log X_t, \Delta \log C_t, \Delta \log \tilde{I}_t, \log L_t, \Delta \log \frac{W_t}{P_t}, \pi_t, R_t, \Delta \log \frac{P_{It}}{P_t}\right] \tag{4.1}$$

as the vector of observable variables, where Δdenotes the temporal difference operator. We use quarterly data from 1954QIII to 2009QI, which is the first quarter in which the policy rate hit the zero bound.

All data are extracted from Haver Analytics. We construct real GDP by diving the nominal series by population and the chain-weighted deflator for consumption of non-durables and services, which, in line with the model, we choose as the numeraire. The real series for consumption and investment are obtained in the same manner. We define consumption as personal consumption expenditures on non-durables and services, while investment is the sum of personal consumption expenditures on durables and gross private domestic investment. We measure the labor input by the log of hours of all persons in the non-farm business sector divided by population, while real wages correspond to nominal compensation per hour in the non-farm business sector, divided by the consumption deflator. The quarterly log difference in the consumption deflator is our measure of inflation. It tracks pretty closely the deflator for aggregate output. For nominal interest rates we use the effective Federal Funds rate.

Finally, the relative price P_{It}/P_t corresponds to the ratio of the chain weighted deflators for consumption and investment as defined above. Hence, for the numerator we rely on National Income and Product Accounts (NIPA) deflators for durable consumption and private investment. Some authors have argued that NIPA's quality adjustments may underestimate the rate of technological progress in areas such as equipment and software (e.g. Gordon, 1990 and Cummins and Violante, 2002). This adjustment problem, in turn, could distort the measured contribution of IST change to both growth and business cycles. For this reason, Greenwood et al. (1997) and Fisher (2006), for example, measure P_{It}—totally or in part—with Gordon's price series for producer durable equipment, as later updated by Cummins and Violante (hereafter the GCV deflator).

For our baseline estimates, we work with NIPA deflators instead, since we want our sample to include the current recession, while the GCV deflator is only available until the end of 2000. Furthermore, the Bureau of Economic Analysis has introduced hedonic price indexes (in partnership with IBM) to control for quality changes in computers and peripherals, starting in 1985. These adjustments have been extended back to 1959 to account for discontinuities, now include additional categories of goods, and deliver price declines in line with other studies based on microdata (e.g. Landefeld and Grimm, 2000).

Nonetheless, we also check the robustness of our results to the use of the GCV deflator, given our focus on the role of the relative price of investment in the identification of investment shocks. To this end, we construct an alternative price index for investment by chain-weighting the price indexes for consumer durables, private investment in residential and non-residential structures (using NIPA deflators) and private equipment and software (using the GCV series).[4] We plot the (log) relative prices of investment to consumption (P_{It}/P_t) resulting from the two measurement procedures (NIPA and GVC) in Fig. 1. The use of the GCV deflator for equipment and software results in a faster rate of decline, as also noted by Fisher (2006). In particular, the mean of $\Delta \log \frac{P_t^I}{P_t}$ from 1954:III to 2000:IV is -0.37 using NIPA data, but -0.51 with the GCV measure.

Both relative prices seem to exhibit a break in trend sometime around 1982:I (denoted by a dashed vertical line in Fig. 1). The mean growth rate of the NIPA relative price falls from -0.15 for the 1954:III–1981:IV period to about -0.6 in the second part of the sample. The corresponding averages for the GCV deflator are -0.3 and -0.78 respectively. To account for this possible break when taking our model to the data, we allow the average growth rate of the IST process to vary before and after 1982:I, while keeping all other parameters unchanged.

4.2. Priors

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 summarizes the priors for the remaining parameters of the model. These priors are relatively disperse and broadly in line with those adopted in previous studies (e.g. Del Negro et al., 2007 and Justiniano and Primiceri, 2008). In

[4] This alternative price index excludes inventories, although they are present in our real investment measure.

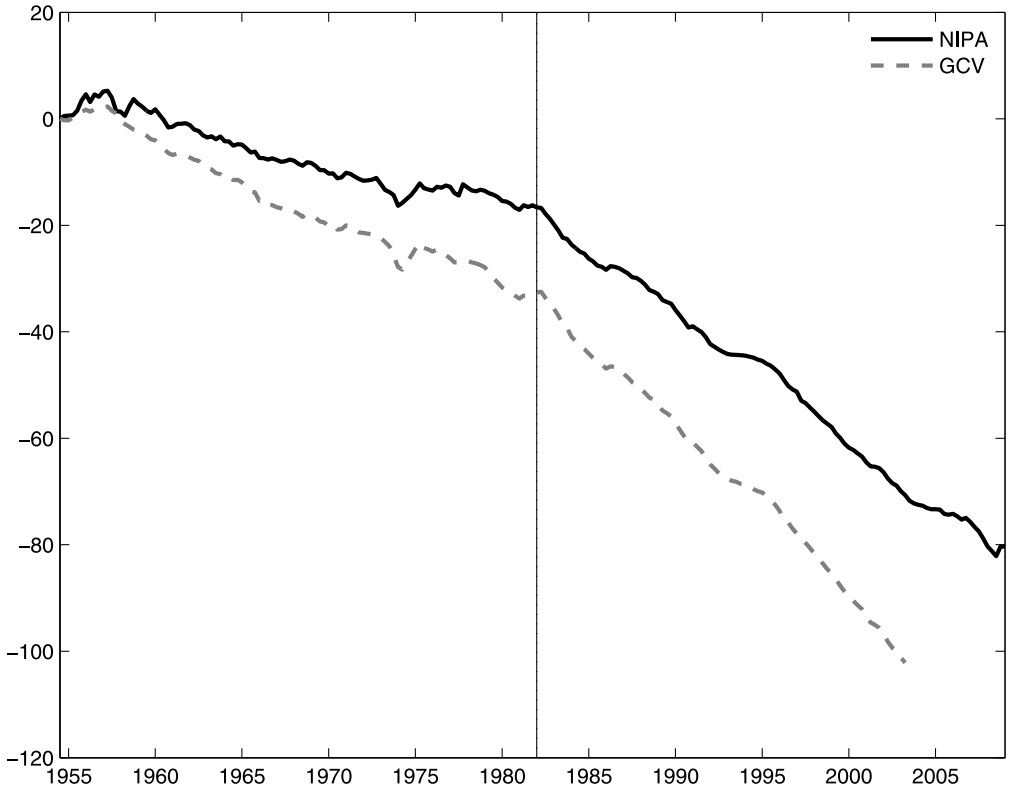


Fig. 1. Alternative measures of the relative price of investment. NIPA is based on the National Income and Product Accounts deflators and is the series used in the baseline estimation. GCV uses the Gordon–Cummins–Violante deflator for equipment and software.

Table 1
Prior densities and posterior estimates for the baseline model.

Coefficient	Description	Prior			Posterior[b]			
		Prior density[a]	Mean	Std	Mode	Median	Std	[5, 95]
α	Capital share	N	0.30	0.05	0.167	0.167	0.006	[0.16, 0.18]
ι_p	Price indexation	B	0.50	0.15	0.097	0.131	0.047	[0.07, 0.22]
ι_w	Wage indexation	B	0.50	0.15	0.096	0.092	0.028	[0.05, 0.14]
γ_*^1	SS composite technology growth rate (first sample)	N	0.40	0.025	0.393	0.394	0.024	[0.35, 0.43]
γ_υ^1	SS IST growth rate (first sample)	N	0.20	0.025	0.185	0.191	0.023	[0.15, 0.23]
γ_*^2	SS composite technology growth rate (second sample)	N	0.30	0.025	0.303	0.300	0.023	[0.27, 0.34]
γ_υ^2	SS IST growth rate (second sample)	N	0.60	0.025	0.597	0.596	0.023	[0.56, 0.63]
h	Consumption habit	B	0.50	0.10	0.859	0.858	0.020	[0.82, 0.89]
λ_p	SS mark-up goods prices	N	0.15	0.05	0.171	0.180	0.038	[0.11, 0.24]
λ_w	SS mark-up wages	N	0.15	0.05	0.135	0.144	0.047	[0.08, 0.23]
$\log L^{ss}$	SS hours	N	0.00	0.50	0.299	0.194	0.492	[−0.55, 1.09]
$100(\pi - 1)$	SS quarterly inflation	N	0.50	0.10	0.702	0.701	0.072	[0.59, 0.83]
$100(\beta^{-1} - 1)$	Discount factor	G	0.25	0.10	0.134	0.149	0.048	[0.08, 0.24]
ν	Inverse frisch elasticity	G	2.00	0.75	4.444	4.492	0.790	[3.26, 5.85]
ξ_p	Calvo prices	B	0.66	0.10	0.778	0.787	0.018	[0.76, 0.82]
ξ_w	Calvo wages	B	0.66	0.10	0.760	0.777	0.035	[0.72, 0.83]
χ	Elasticity capital utilization costs	G	5.00	1.00	5.434	5.672	0.983	[4.18, 7.41]
S''	Investment adjustment costs	G	4.00	1.00	2.657	3.142	0.292	[2.64, 3.64]
Φ_p	Taylor rule inflation	N	1.70	0.30	1.709	1.688	0.127	[1.48, 1.9]
Φ_y	Taylor rule output	N	0.13	0.05	0.051	0.046	0.015	[0.03, 0.08]
Φ_{dy}	Taylor rule output growth	N	0.125	0.05	0.208	0.211	0.020	[0.18, 0.25]
ρ_R	Taylor rule smoothing	B	0.60	0.20	0.858	0.860	0.015	[0.84, 0.88]

(*continued on the next page*)

Table 1 (*continued*)

Coefficient	Description	Prior			Posterior[b]			
		Prior density[a]	Mean	Std	Mode	Median	Std	[5, 95]
ρ_z	Neutral technology growth	B	0.40	0.20	0.286	0.287	0.048	[0.21, 0.36]
ρ_g	Government spending	B	0.60	0.20	0.990	0.989	0.001	[0.99, 0.99]
ρ_υ	Investment specific technology growth	B	0.20	0.10	0.156	0.163	0.054	[0.07, 0.25]
ρ_p	Price mark-up	B	0.60	0.20	0.971	0.975	0.008	[0.96, 0.99]
ρ_w	Wage mark-up	B	0.60	0.20	0.967	0.962	0.007	[0.95, 0.97]
ρ_b	Intertemporal preference	B	0.60	0.20	0.590	0.614	0.034	[0.56, 0.67]
ρ_μ	Marginal efficiency of investment	B	0.60	0.20	0.772	0.813	0.020	[0.77, 0.85]
θ_p	Price mark-up MA	B	0.50	0.20	0.989	0.984	0.002	[0.98, 0.99]
θ_w	Wage mark-up MA	B	0.50	0.20	0.831	0.827	0.032	[0.77, 0.88]
σ_{mp}	Monetary policy	I	0.10	1.00	0.210	0.210	0.011	[0.19, 0.23]
σ_z	Neutral technology growth	I	0.50	1.00	0.933	0.943	0.045	[0.88, 1.03]
σ_g	Government spending	I	0.50	1.00	0.365	0.369	0.020	[0.34, 0.41]
σ_υ	Investment specific technology growth	I	0.50	1.00	0.630	0.629	0.030	[0.59, 0.68]
σ_p	Price mark-up	I	0.10	1.00	0.219	0.222	0.018	[0.2, 0.26]
σ_w	Wage mark-up	I	0.10	1.00	0.310	0.316	0.017	[0.28, 0.34]
σ_b	Intertemporal preference	I	0.10	1.00	0.036	0.034	0.002	[0.03, 0.04]
σ_μ	Marginal efficiency of investment	I	0.50	1.00	5.103	5.786	0.248	[5.3, 6.2]
(*log*) *Likelihood*					−1448.9	−1452.3		
(*log*) *Posterior*					−1466.7	−1469.2		

Note: Calibrated coefficients: $\delta = 0.025$, g implies a SS government share of 0.22. Relative to the text, the standard deviations of the innovations (σ) are scaled by 100.

[a] N stands for Normal, B—Beta, G—Gamma and I—Inverted-Gamma1 distribution.

[b] Median and posterior percentiles are from 2 chains of 80,000 draws generated using a Random Walk Metropolis algorithm. We discard the initial 50,000 and retain one every 5 subsequent draws.

particular, we retain the same priors as in JPT's baseline model, except for the coefficients of the IST process, which does not appear in that model.

In line with the evidence in Fig. 1, we allow for different Gaussian priors for the IST growth rates pre and post-1982, γ_υ^1 and γ_υ^2 respectively. We adopt a similar approach for the growth rates of the composite trend γ_*, given that it depends on γ_υ, and that all real series grow at a lower rate in the second sub-sample.

For most persistence parameters, we use a Beta prior with mean 0.6 and standard deviation 0.2. For the autocorrelation of neutral (z) and investment-specific (υ) technology shocks instead we center the prior at 0.4 and 0.2 respectively, since these processes already include a unit root.

Regarding the remaining shocks, the intertemporal preference, price and wage markup shocks are normalized to enter with a unit coefficient in the consumption, price inflation and wage equations respectively. The priors on the innovations' standard deviations are quite disperse and chosen to generate volatilities for the endogenous variables broadly in line with the data. The covariance matrix of the innovations is diagonal.

5. Estimation results

This section presents our main results in terms of parameter estimates, impulse responses and business cycle variance decomposition.

5.1. Posteriors: parameters and impulse responses

The last column of Table 1 reports the posterior estimates of the model's parameters. Most estimates are in line with previous DSGE studies and change very little relative to JPT's baseline. Perhaps surprisingly, the MEI shock μ_t remains quite volatile, even if the IST shock now also perturbs the investment Euler equation.

By construction, the properties of the IST shock are consistent with those of the relative price of investment. In particular, the average growth rates of the IST process are 0.19% and 0.60% in the first and second subsamples respectively. Therefore, according to our estimates, technological improvements specific to the investment goods producing sector are responsible for approximately 10% of economic growth in 1954–1982 and for about 40% in 1983–2008.

To provide another perspective on the comparability of the posterior estimates in Table 1 with those in the literature, Fig. 2 displays the impulse responses to the MEI shock μ_t. Following a positive shock, output, hours, and investment all rise persistently and in a hump-shaped pattern. The same happens to wages, even if the posterior estimate of the dynamic indexation parameter ι_w is very low. On the contrary, consumption increases only after a few periods. The fact that these

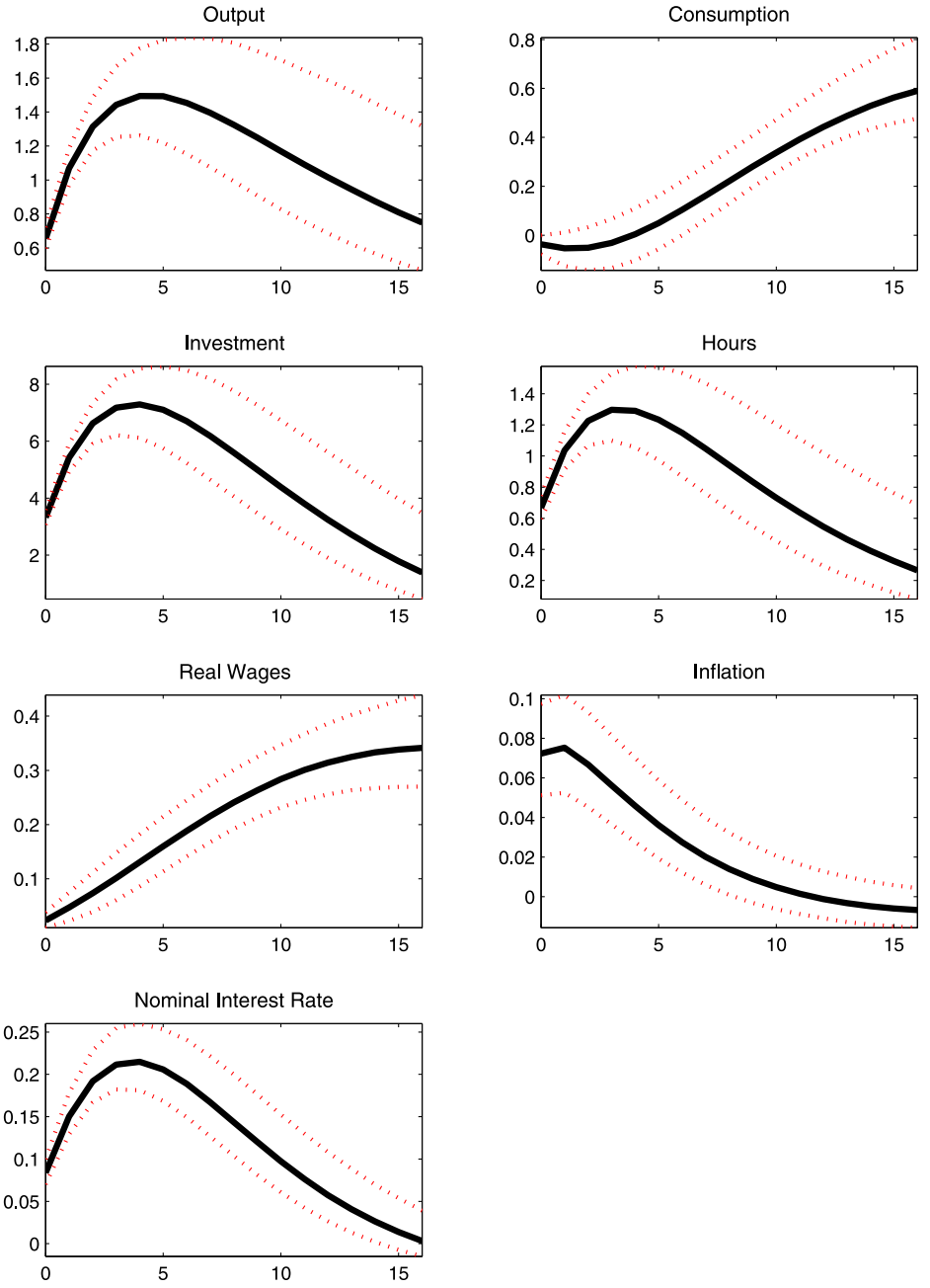


Fig. 2. Impulse responses to a one standard deviation marginal efficiency of investment (MEI) shock. The solid line is the median, while the dotted lines are the 5th and 95th percentiles.

responses closely resemble those in JPT suggests that the observability of the relative price of investment does not affect significantly the inference on the MEI shock μ_t. This conclusion is confirmed in the next sections, where we study the contribution of all shocks to business cycle fluctuations.

5.2. Model's fit

Given our posterior estimates, how well does the model fit the data? 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 2 reports the standard deviation of our eight observable variables, in absolute terms as well as relative to that of output growth. For the model, we report the median and the 90 percent probability intervals that account for both

Table 2
Standard deviations and correlations for observable variables in the baseline model.

Series	Standard deviation			Autocorrelation		
	Data	Baseline model		Data	Baseline model	
		Median	[5th, 95th]		Median	[5th, 95th]
Output growth	0.96	1.17	[1.02, 1.35]	0.35	0.61	[0.50, 0.70]
Consumption growth	0.48	0.67	[0.57, 0.79]	0.38	0.65	[0.54, 0.73]
Investment growth	3.57	4.93	[4.19, 5.79]	0.30	0.66	[0.56, 0.75]
Hours	3.68	4.77	[3.41, 6.94]	0.95	0.96	[0.94, 0.98]
Wage growth	0.63	0.75	[0.67, 0.84]	0.12	0.30	[0.16, 0.43]
Inflation	0.63	0.53	[0.45, 0.64]	0.77	0.69	[0.57, 0.79]
Interest rates	0.83	0.72	[0.56, 0.95]	0.95	0.93	[0.89, 0.95]
Relative price	0.64	0.64	[0.57, 0.72]	0.14	0.15	[0.01, 0.29]
Series	Standard deviation relative to output			Correlation with output growth		
	Data	Baseline model		Data	Baseline model	
		Median	[5th, 95th]		Median	[5th, 95th]
Consumption growth	0.50	0.57	[0.48, 0.68]	0.58	0.40	[0.23, 0.54]
Investment growth	3.71	4.21	[3.81, 4.66]	0.89	0.85	[0.79, 0.89]
Hours	3.83	4.08	[3.06, 5.59]	0.08	0.15	[0.04, 0.27]
Wage growth	0.66	0.64	[0.55, 0.75]	0.24	0.33	[0.19, 0.46]
Inflation	0.66	0.46	[0.37, 0.56]	−0.37	−0.13	[−0.31, 0.07]
Interest rates	0.86	0.62	[0.49, 0.79]	−0.22	0.01	[−0.20, 0.20]
Relative price	0.67	0.54	[0.46, 0.65]	−0.17	−0.06	[−0.18, 0.06]

parameter and small-sample uncertainty. The model overpredicts the volatility and the first order autocorrelation of output, consumption and investment growth, but it matches fairly well their standard deviations relative to output growth, as well as their correlation with this variable. The match with hours is close for both the volatilities and the autocorrelations, while the model's 90 percent posterior probability intervals encompass the standard deviations and persistence of both inflation and the nominal interest rate. Moreover, the model accounts well for the properties of the relative price.

With as many shocks as observable variables, why does the model not capture their standard deviation and autocorrelation perfectly? The reason is that a likelihood-based estimator tries to match the entire autocovariance function of the data, and thus must strike a balance between matching standard deviations, first order autocorrelations and all the other second moments. These other moments are displayed in Fig. 3, for the data (grey line) and the model (back line), along with the 90 percent posterior intervals for the model implied by parameter and small-sample uncertainty.

Focus first on the upper-left 4-by-4 block of graphs, 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 reasonably well. The success is particularly impressive for hours, for which the data and model-implied autocorrelations lay virtually on top of each other. In terms of cross-correlations, the model does a fairly good job for output (the first row and column) and especially 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.

With respect to prices, the model is overall quite successful in reproducing the main stylized facts. We emphasize two issues: first, the model does not 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, the model matches quite well the correlation between the relative price of investment and the real variables, especially output, consumption and investment, as shown in the last row of Fig. 3.

5.3. Investment shocks and business cycles

In this section, we present the variance decomposition for our model at business cycle frequencies and compare it to that in JPT.

Table 3 reports the contribution of the eight shocks in the model to the variance of macroeconomic variables at business cycle frequencies. The first result we want to stress is that IST progress plays virtually no role in business cycles, although it is crucial to long-run growth. This result is in line with the findings in Schmitt-Grohe and Uribe (2008). In a real model with frictions similar to ours, they find that IST shocks—contemporaneous or anticipated—account for 0 percent of the fluctuations in output, consumption, investment and hours. They also identify IST progress with the relative price of investment, as we do here.

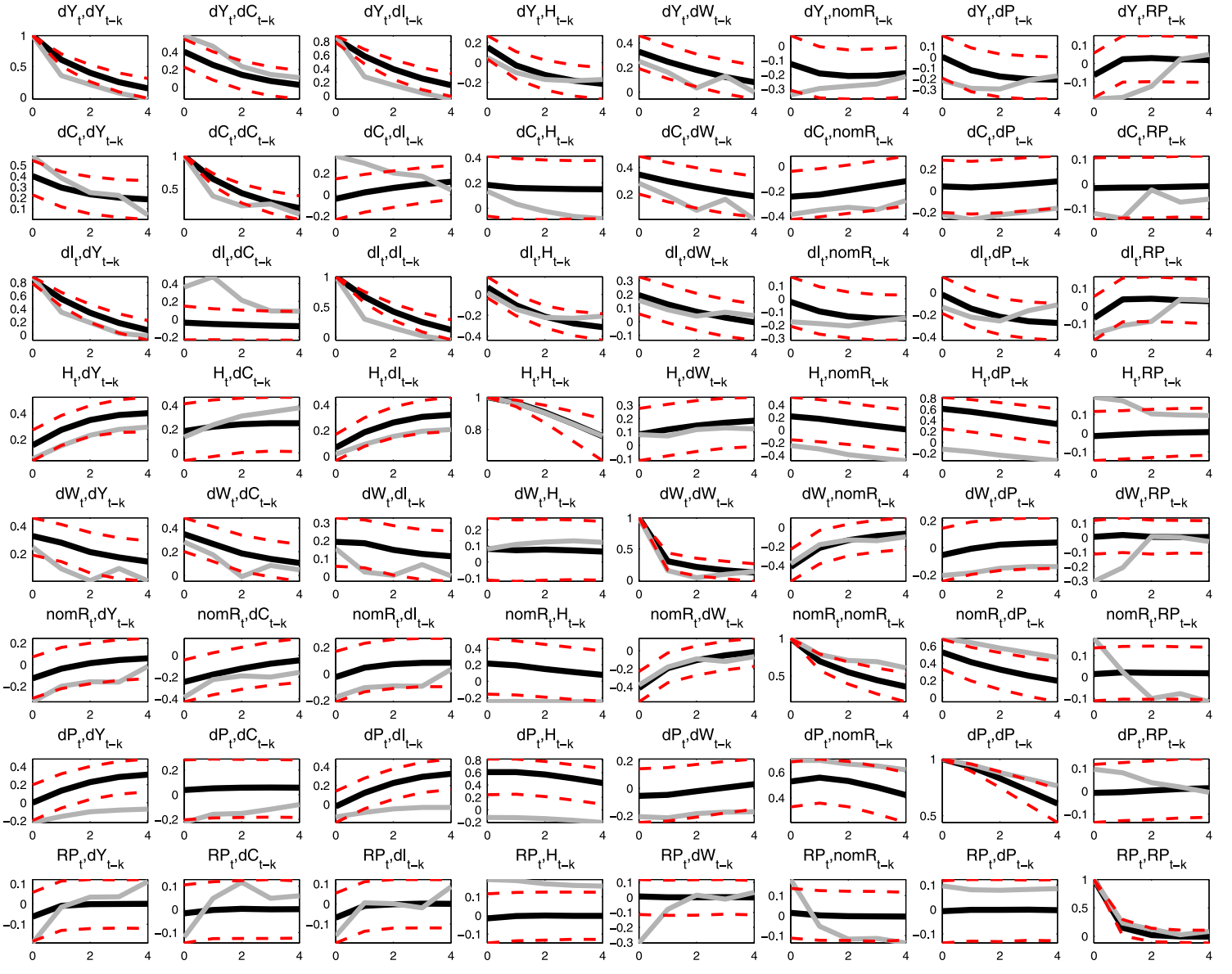


Fig. 3. Cross-correlogram of the observable variables in the baseline model and the data. The light grey line is the data. The solid line is the model's median and the dashed lines are the model's 5th and 95th percentiles.

Table 3
Variance decomposition at business cycle frequencies[a] in the baseline model.

Series/shock	Monetary policy	Neutral technology	Government	Investment specific technology	Price mark-up	Wage mark-up	Intertemporal preference	Marginal efficiency of investment
Output	0.04 [0.03, 0.06]	0.25 [0.20, 0.33]	0.02 [0.02, 0.03]	0 [0.00, 0.00]	0.02 [0.01, 0.03]	0.01 [0.01, 0.01]	0.05 [0.04, 0.07]	0.6 [0.52, 0.67]
Consumption	0.02 [0.01, 0.03]	0.31 [0.24, 0.39]	0.02 [0.02, 0.03]	0 [0.00, 0.00]	0 [0.00, 0.00]	0.01 [0.00, 0.02]	0.55 [0.45, 0.64]	0.08 [0.05, 0.14]
Investment	0.02 [0.02, 0.03]	0.08 [0.06, 0.12]	0 [0.00, 0.00]	0 [0.00, 0.01]	0.02 [0.01, 0.03]	0.01 [0.01, 0.01]	0.01 [0.00, 0.02]	0.85 [0.80, 0.89]
Wages	0 [0.00, 0.00]	0.54 [0.44, 0.61]	0 [0.00, 0.00]	0 [0.00, 0.00]	0.23 [0.18, 0.29]	0.21 [0.16, 0.27]	0 [0.00, 0.00]	0.02 [0.01, 0.03]
Relative price	0 [0.00, 0.00]	0 [0.00, 0.00]	0 [0.00, 0.00]	1 [1.00, 1.00]	0 [0.00, 0.00]	0 [0.00, 0.00]	0 [0.00, 0.00]	0 [0.00, 0.00]
Hours	0.05 [0.03, 0.07]	0.13 [0.11, 0.16]	0.02 [0.02, 0.03]	0 [0.00, 0.00]	0.03 [0.02, 0.04]	0.01 [0.01, 0.02]	0.06 [0.05, 0.08]	0.68 [0.63, 0.74]
Inflation	0.03 [0.02, 0.05]	0.37 [0.26, 0.45]	0 [0.00, 0.00]	0 [0.00, 0.00]	0.39 [0.32, 0.48]	0.08 [0.05, 0.14]	0.02 [0.01, 0.03]	0.1 [0.06, 0.17]
Interest rates	0.14 [0.11, 0.18]	0.14 [0.10, 0.17]	0.01 [0.01, 0.01]	0 [0.00, 0.00]	0.03 [0.02, 0.04]	0.02 [0.01, 0.03]	0.11 [0.08, 0.15]	0.56 [0.49, 0.63]

[a] Business cycle frequencies correspond to periodic components with cycles between 6 and 32 quarters. The decomposition is obtained using the spectrum of the DSGE model and an inverse first difference filter for output, consumption, investment and wages to reconstruct the levels. The spectral density is computed from the state space representation of the model with 5000 bins for frequencies covering that range of periodicities. Medians need not add up to one.

The second important result that emerges from Table 3 is that MEI shocks are the key drivers of business cycle fluctuations. They are responsible for 60, 68 and 85 percent of the variance of GDP, hours and investment respectively, although they explain little of consumption variability. These shares are similar (50, 65 and 80) when we use the GCV price of equipment to construct the investment deflator on a shorter sample.

To assess the role of the priors in these results, Fig. 4 compares the prior and posterior densities for the variance share of output, hours, consumption and investment explained by MEI shocks over the business cycle. The a priori probability that MEI shocks account for a large fraction of macroeconomic fluctuations is quite low, pointing to the importance of the likelihood information for the posterior variance decomposition.

The conclusion we draw from this evidence is that making the relative price of investment observable has almost no impact on the view of business cycles presented in JPT, as long as we recognize that not all investment shocks must be reflected in the relative price of investment.

The negligible role of IST shocks in our estimates deserves some qualification, especially since Fisher (2006) finds that these disturbances account for a considerable share of the variation of output and hours. Fisher's (2006) identification relies on the assumption that IST shocks are the only drivers of permanent changes in the relative price, but admits short-run deviations between the two. Our model, on the contrary, imposes a straightjacket on these shocks: they must equal the observed relative price of investment period by period. But this equality would not hold in richer, and arguably more realistic, environments.

For example, in an economy in which the production of investment goods employs capital and labor as inputs, and faces the same kind of nominal rigidity as that of consumption, the relative price of investment is influenced by IST progress, but also by other disturbances. This is because the markups in the two sectors will differ over the cycle, due to the sector-specific nature of technological change, and thus of marginal costs. The ratio of these two markups would thus create a wedge between the relative price of investment and the inverse of the IST shock, as illustrated in Appendix A.

Another relevant difference between our empirical approach and that of Fisher (2006) is that his investment deflator only includes the price of equipment, as measured by GCV. On the contrary, we use the price of durable consumption plus gross private domestic investment, since this matches the definition of investment expenditures in our model. Given that the price of equipment is more clearly countercyclical, Fisher's (2006) choice enhances the importance of IST shocks for business cycles, as noted in Fisher (2005). This observation also helps to reconcile our results with those of Greenwood et al. (2000), who calibrate a DSGE model with real rigidities using the price of equipment and find that IST shocks account for about 10 percent of the variance of output.[5]

[5] Greenwood et al. (2000) report that, in their calibration, IST shocks alone can produce fluctuations in output with a standard deviation equal to 30 percent of that of GDP, which corresponds to 9 percent of its variance.

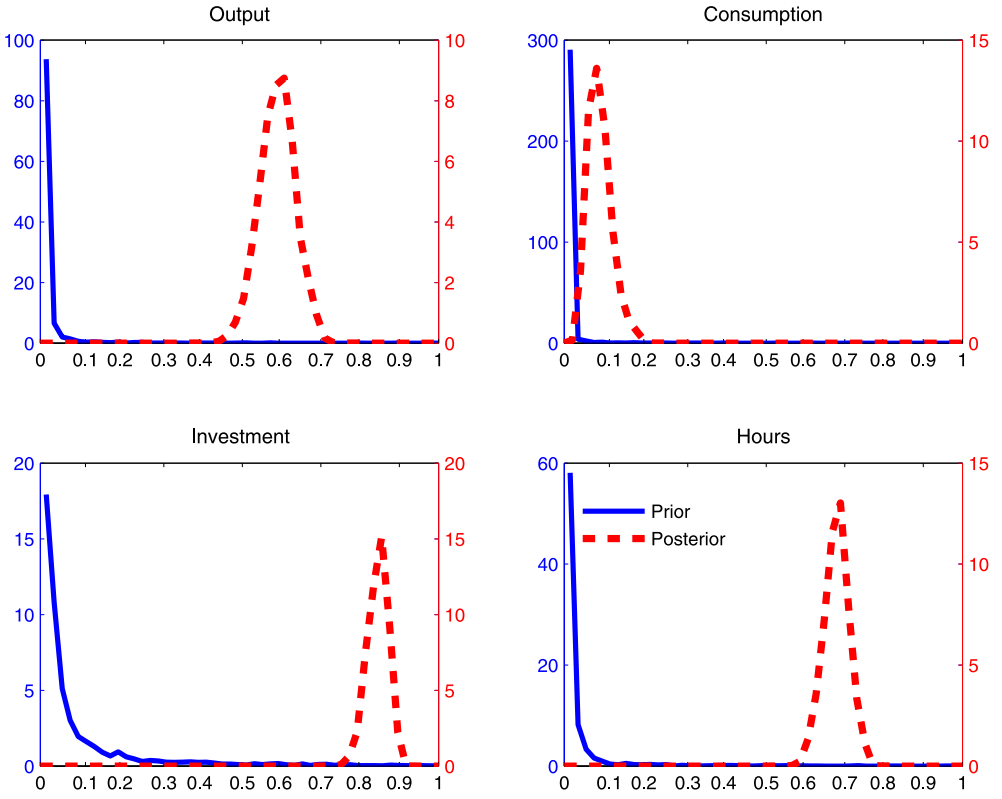


Fig. 4. Prior and posterior densities of the shares of the variance of output growth, consumption growth, investment growth, and the level of hours accounted for by the marginal efficiency of investment shock.

6. Interpreting the results: What is μ_t?

In Section 5, we found that business cycles are driven primarily by shocks that affect the transformation of investment goods into installed capital (MEI shocks), rather than that of consumption into investment goods (IST shocks). In the model, the MEI shocks represent disturbances to the process by which investment goods—idle pieces of machinery just pushed out the door of the factory that produced them—are turned into capital ready for production. This process entails a waste of physical resources when adjusting the rate of investment, as well as some randomness captured by μ_t. Sometimes the creation of productive capital is a smooth and efficient process, sometimes it is not.

In the real world, the financial system plays a crucial role in this process. For example, if capital producers must borrow to purchase investment goods, the creation of productive capital will be affected by their ability to access credit, as well as by the efficiency with which the financial system allocates that credit, as, for instance, in the models of Barlevy (2003) and Matsuyama (2007). In our model, there is no explicit role for financial intermediation, since we assume that households purchase installed capital directly from its producers. However, the transformation of foregone consumption (real saving) into future productive capital depends on its relative price, which in equilibrium is affected by μ_t. Negative shocks to μ_t decrease the amount of effective capital installed per unit of foregone consumption. Thus, one possible interpretation of the random term μ_t is as a proxy for the effectiveness with which the financial sector channels the flow of household savings into new productive capital.

To be more specific, it is useful to refer to the financial accelerator model of Carlstrom and Fuerst (1997).[6] In their model, entrepreneurs are the only agents with access to the technology for the production of installed capital. To finance their activity, entrepreneurs borrow from households through competitive intermediaries, but their idiosyncratic productivity is private information. The costs associated with the need to monitor the failing projects result in the destruction of some units of investment goods and thus represent a drain on the capital formation process, so that the (physical) capital accumulation equation takes the form

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + (1-\Phi_t)I_t, \tag{6.1}$$

[6] Chari et al. (2007) demonstrate the equivalence between the economy of Carlstrom and Fuerst (1997) and a prototypical growth model with an investment wedge very similar to our investment shock μ_t.

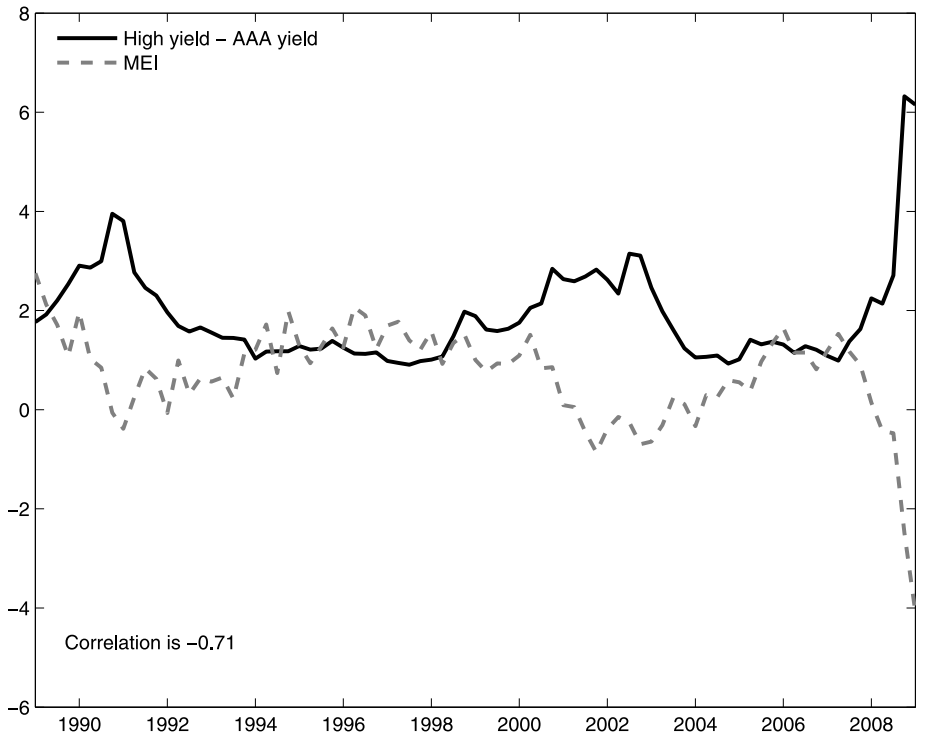


Fig. 5. Credit spread and the marginal efficiency of investment. The credit spread (dark continuous line) is measured as the difference between the returns on high yield and AAA corporate bonds. The marginal efficiency of investment series (light dashed line) is the Kalman filter estimate of the μ_t shock at the posterior mode. Both series are standardized.

where Φ_t is the aggregate amount of new capital destroyed by monitoring, which in equilibrium depends on the endogenous default rate, and thus on entrepreneurs' net worth. This expression compares to our accumulation equation

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + \mu_t(1-S_t)I_t.$$

In these two equations, both the MEI shock μ_t, net of the adjustment costs S_t, and the agency cost $\Phi_t$interfere with the transformation of investment goods into physical capital.

In fact, Carlstrom and Fuerst (1997) point out that their framework "is isomorphic to a model in which there are costs to adjusting the capital stock," if net worth is held constant. More precisely, their assumptions result in a supply curve for new productive capital (i in our notation), which is upward sloping in the relative price of capital and is shifted by changes in entrepreneurial net worth. Intuitively, an increase in entrepreneurs' net worth lowers leverage, the default probability and the external finance premium, therefore boosting the supply of new capital goods. In our model, the MEI shock plays—in reduced form—a similar economic role to that of net worth in Carlstrom and Fuerst (1997), since it also acts as a shifter of the capital supply function. The important difference is that μ_t is just an exogenous shock in our framework, while net worth is a key endogenous variable in the agency cost model.

Fig. 5 sheds more light on the relationship between the two models, by comparing the behavior of the μ_t series implied by our estimation to that of a proxy for the external finance premium, namely the spread between the returns on high-yield and AAA corporate bonds, as measured by Merrill Lynch's Corporate High-Yield Master II Index and Moody's Seasoned AAA Corporate Bond Yield, respectively. This spread is only available starting in 1988, when the high-yield bond market took off. However, we prefer this series to the available alternatives with a longer history, because of its high predictive content for economic activity (e.g. Gertler and Lown, 1999), which is close to that of the returns on corporate bonds in the middle of the credit quality spectrum recently emphasized by Gilchrist et al. (2009). In fact, Gilchrist and Zakrajsek (2008) show that high yield spreads are particularly effective in forecasting employment and investment, which are the variables for which the MEI shock has the highest explanatory power in our model.[7]

The posterior mode of μ_t and our spread measure display a strong negative correlation (-0.71, which becomes -0.5 if we drop the last two points), indicating that MEI shocks indeed tend to be negative when the functioning of financial markets is impaired, as proxied by high spreads. In particular, the spike in spreads in 2008QIV is associated with a large negative realization of the MEI shock.

[7] The measures of yield spreads used in the literature as proxies for the external finance premium vary widely, but they are all similarly countercyclical. We prefer a spread to a triple A corporate index, rather than to Treasury bonds, because the latter contain a liquidity premium that is also countercyclical.

The ex-post correlation highlighted in Fig. 5 is only suggestive of the possible origin of the MEI shock and might simply reflect the fact that both μ_t and the spread are good business cycle indicators. To push our interpretation further, we re-estimated the model including our measure of the spread among the observables, as a direct source of information on the MEI process. In particular, we linked the two through the following measurement equation

$$spread_t = \kappa \mu_t + \epsilon_t,$$

where κ is a constant of proportionality and ϵ_t is a measurement error.

This statistical model for μ_t is again inspired by Carlstrom and Fuerst's (1997) formulation of the financial accelerator. In their framework, the equilibrium monitoring costs, represented by Φ_t in Eq. (6.1), increase with the incidence of default, which is in turn positively related to the premium charged by financial intermediaries to cover that risk. Therefore, the model suggests a positive link between the marginal efficiency of investment and the external finance premium, which we proxy with the measure of the high-yield spread depicted in Fig. 5. This empirical experiment, although admittedly crude, has the added advantage of imposing some discipline on the inference on μ_t, even if a more fully spelled out model would also generate cross-equation restrictions on the coefficient of proportionality κ. Here we remain completely agnostic about the value of κ through a flat prior. As for the standard deviation of the measurement error, the prior is an Inverse-Gamma with mean equal to 0.2, which is about 10 percent of the standard deviation of the high-yield spread.[8]

The posterior estimate of κ is equal to 0.31, and the MEI shock accounts for 82 of the cyclical variation in the spread, with the remaining 18 percent picked up by the measurement error, as shown in Table 4. From the same table, we see that the MEI shock explains 37, 41 and 79 percent of the variance of output, hours and investment at business cycle frequencies. These shares are somewhat lower than in the estimation with μ_t unconstrained, as we would expect. However, the results of this experiment, corroborate the interpretation of MEI shocks as a proxy for the overall health of the financial system.

The last piece of evidence in support of this interpretation is presented in Fig. 6, which focuses on the contribution of MEI shocks to the recession of 2008–2009. This is a useful reality check, since most observers would agree that this recession, and the slowdown in growth that preceded it, were triggered and further propagated by a sequence of disruptions in financial markets.

Starting right after the through of the last recession (2001QIV), the figure compares the evolution of output and hours in the data (the solid line) and in the counterfactual scenario with only MEI shocks. The dashed lines represent this counterfactual in the baseline model, while the dotted lines refer to the model estimated with the high-yield spread. The models include many shocks that together replicate the data exactly. Therefore, it is not surprising that the MEI shock alone does not track the ups and downs of the two series perfectly. However, the coherence in the movements of the actual and counterfactual lines over the cycle is remarkable. In particular, μ_t generates a fall in the growth rate of output and hours that starts in 2006 and accelerates in 2008, replicating the depth of the recession as of the end of 2008, particularly in hours.

7. Concluding remarks

In this paper, we showed that identifying all disturbances to the process of capital accumulation with the inverse of the relative price of investment can lead to misleading inferences on the role of these shocks in business cycles. We presented a simple model in which the transformation of consumption goods into investment goods and of the latter into productive capital are both affected by stochastic shocks. The contributions of these two shocks to macroeconomic fluctuations can be disentangled because only the former—investment-specific technology shocks—affect the relative price of investment. In an estimated version of this model, shocks to the production of the capital input—marginal efficiency of investment shocks—emerge as the predominant sources of variability in the key macroeconomic variables at business cycle frequencies.

Our estimated model has three main shortcomings, which we plan to address in the near future. First, it implies a countercyclical price of capital. Addressing this problem requires a more elaborate model of the capital accumulation process, as in Christiano et al. (2007) and Comin et al. (2009), or of the frictions that impede the reallocation of resources across sectors (e.g. Christiano and Fisher, 2003).

Second, the short-run comovement of consumption with the other macroeconomic variables conditional on MEI shocks is weak, as shown in JPT. As a result, these shocks account for only a small fraction of the variance of consumption. Several recent contributions analyze mechanisms with the potential to solve this comovement problem (Jaimovich and Rebelo, 2009; Eusepi and Preston, 2009; Furlanetto and Seneca, 2009; Khan and Tsoukalas, 2009).

Third, a very active strand of the literature on the sources of fluctuations focuses on the contribution of news shocks. This literature includes the seminal contribution of Beaudry and Portier (2006), which pointed to the empirical importance of these shocks, as well as work in general equilibrium environments by Davis (2007), Christiano et al. (2007), Schmitt-Grohe and Uribe (2008) and Jaimovich and Rebelo (2009). The mechanisms through which anticipated shocks can generate comovement among macroeconomic variables are similar to those transmitting investment shocks. Therefore, incorporating news shocks in our framework should prove an interesting avenue for future research.

[8] For symmetry, in this model we also add a measurement error with a similar prior to the observation equation of the relative price of investment.

Table 4
Variance decomposition at business cycle frequencies[a] in the model with high-yield spread observable.

Series/shock	Monetary policy	Neutral technology	Government	Investment specific technology	Price mark-up	Wage mark-up	Intertemporal preference	Marginal efficiency of investment	Measurement error in relative price	Measurement error in spread
Output	0.03 [0.02, 0.04]	0.34 [0.26, 0.42]	0.04 [0.03, 0.06]	0.00 [0.00, 0.00]	0.08 [0.05, 0.13]	0.03 [0.01, 0.06]	0.10 [0.07, 0.14]	0.37 [0.30, 0.45]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Consumption	0.02 [0.01, 0.03]	0.44 [0.34, 0.54]	0.01 [0.01, 0.02]	0.00 [0.00, 0.00]	0.03 [0.01, 0.06]	0.01 [0.01, 0.02]	0.43 [0.33, 0.55]	0.04 [0.02, 0.09]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Investment	0.01 [0.01, 0.02]	0.09 [0.06, 0.13]	0.00 [0.00, 0.00]	0.01 [0.00, 0.01]	0.06 [0.04, 0.10]	0.04 [0.02, 0.06]	0.00 [0.00, 0.00]	0.79 [0.74, 0.82]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Wages	0.00 [0.00, 0.00]	0.45 [0.33, 0.57]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.32 [0.18, 0.46]	0.23 [0.13, 0.29]	0.00 [0.00, 0.00]	0.01 [0.00, 0.02]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Relative price	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.99 [0.98, 1.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.01 [0.00, 0.02]	0.00 [0.00, 0.00]
Hours	0.03 [0.02, 0.05]	0.22 [0.16, 0.30]	0.05 [0.04, 0.07]	0.00 [0.00, 0.00]	0.10 [0.06, 0.16]	0.04 [0.02, 0.07]	0.12 [0.09, 0.17]	0.41 [0.33, 0.50]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Inflation	0.02 [0.01, 0.04]	0.20 [0.13, 0.28]	0.01 [0.00, 0.02]	0.00 [0.00, 0.01]	0.51 [0.38, 0.63]	0.12 [0.06, 0.19]	0.03 [0.02, 0.06]	0.10 [0.04, 0.18]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
Interest rates	0.11 [0.08, 0.15]	0.16 [0.12, 0.22]	0.02 [0.01, 0.04]	0.00 [0.00, 0.01]	0.08 [0.05, 0.13]	0.05 [0.02, 0.10]	0.16 [0.12, 0.22]	0.40 [0.31, 0.49]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]
High yield spread	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.00 [0.00, 0.00]	0.82 [0.77, 0.87]	0.00 [0.00, 0.00]	0.18 [0.13, 0.23]

[a] Business cycle frequencies correspond to periodic components with cycles between 6 and 32 quarters. The decomposition is obtained using the spectrum of the DSGE model and an inverse first difference filter for output, consumption, investment and wages to reconstruct the levels. The spectral density is computed from the state space representation of the model with 5000 bins for frequencies covering that range of periodicities. Medians need not add up to one.

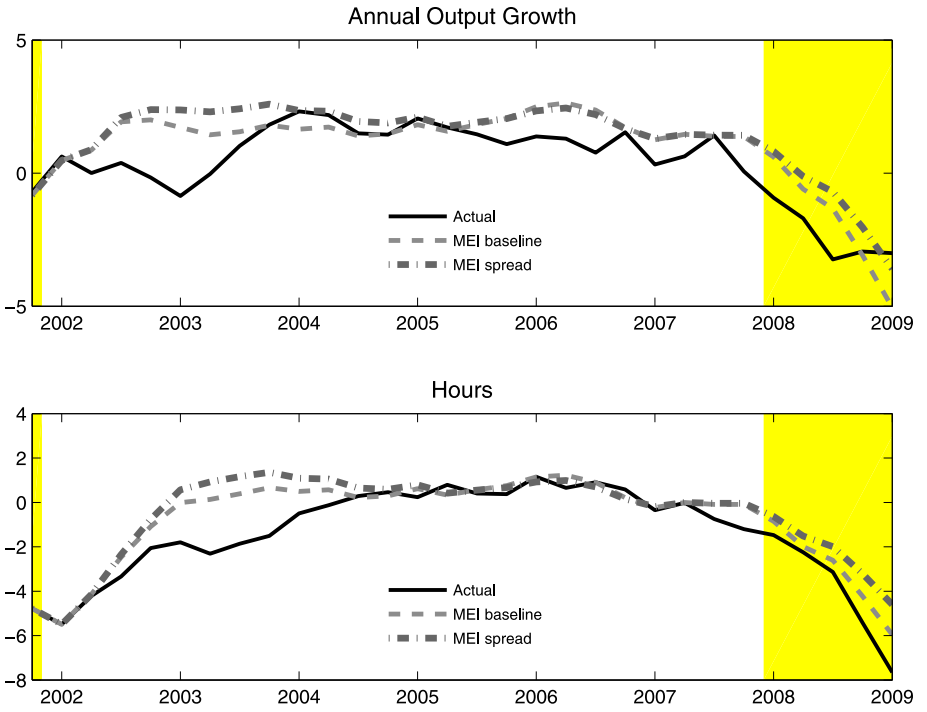


Fig. 6. Contribution of marginal efficiency of investment shocks to the 2008–2009 recession. The dark solid line is the data. The light dashed line (MEI baseline) is the counterfactual with only the MEI shocks in the baseline model. The light dashed-dotted line (MEI spread) is the same counterfactual in the model with the credit spread observable.

Appendix A. IST and the relative price: The case of sticky prices

In this appendix, we develop a more articulated model of the production of consumption and investment goods than the one presented in the main text. In particular, we assume that both goods are produced using capital and labor as inputs by a continuum of monopolistically competitive firms. Moreover, all these firms face a time-dependent constraint on their ability to reset prices, as for the intermediate-goods producing firms in the text. Compared to the baseline model, we strip away some complications, which are immaterial to the conclusions.

Our objective is to show that, in a model of this kind, the relative price of investment in terms of consumption is in general not equal to the inverse of the investment-specific technology factor.

A.1. Consumption and investment producers

A continuum of monopolistically competitive firms produces consumption goods according to the technology

$$C_t(j) = \left[A_t L_{Ct}(j)\right]^{1-\alpha} K_{Ct}(j)^{\alpha},$$

where we are ignoring the presence of fixed costs.

Similarly, the production of investment goods follows

$$I_t(j) = \Upsilon_t \left[A_t L_{It}(j)\right]^{1-\alpha} K_{It}(j)^{\alpha},$$

where Υ_t denotes IST progress. These two kinds of intermediate goods are aggregated into final consumption and investment goods by competitive firms, as in the baseline model.

The capital and labor inputs are homogeneous and command a wage W_t and a rate of return r_t^k respectively. As a result, cost minimization by intermediate firms yields first order conditions

$$MC_{Ct}(j)(1-\alpha)A_t^{1-\alpha}\left(\frac{K_{Ct}(j)}{L_{Ct}(j)}\right)^{\alpha} = W_t,$$

$$MC_{Ct}(j)\alpha A_t^{1-\alpha}\left(\frac{K_{Ct}(j)}{L_{Ct}(j)}\right)^{\alpha-1} = r_t^k$$

in the consumption sector and

$$MC_{It}(j)(1-\alpha)\Upsilon_t A_t^{1-\alpha}\left(\frac{K_{It}(j)}{L_{It}(j)}\right)^{\alpha} = W_t,$$

$$MC_{It}(j)\alpha\Upsilon_t A_t^{1-\alpha}\left(\frac{K_{It}(j)}{L_{It}(j)}\right)^{\alpha-1} = r_t^k$$

in the investment sector, where MC denotes the nominal marginal cost. The homogeneity of factor markets implies that the capital labor ratio is the same for all firms and sectors

$$\frac{K_{It}(j)}{L_{It}(j)} = \frac{K_{Ct}(j)}{L_{Ct}(j)} = \frac{\alpha}{1-\alpha}\frac{W_t}{r_t^k}$$

$\forall j$, which implies the following relationship between marginal costs across sectors

$$\frac{MC_{It}}{MC_{Ct}} = \Upsilon_t^{-1}. \tag{A.1}$$

In a perfectly competitive environment with flexible prices, price is always equal to marginal cost, from which we would obtain that the relative price of investment is equal to the inverse of IST progress

$$\frac{P_{It}}{P_{Ct}} = \Upsilon_t^{-1}.$$

The identical constant returns to scale production functions and the free flow of inputs between the two sectors imply that the rate of transformation between consumption and investment goods in the flexible price equilibrium is simply Υ_t, as in our baseline model.

A.2. Sticky prices and the relative price wedge

When prices are sticky in both sectors, it is useful to rewrite (A.1) as

$$\frac{s_{It}P_{It}}{s_{Ct}P_{Ct}} = \Upsilon_t^{-1},$$

where s denotes the real marginal cost, or the inverse of the equilibrium markup. This implies

$$\frac{P_{It}}{P_{Ct}} = \frac{s_{Ct}}{s_{It}}\Upsilon_t^{-1}, \tag{A.2}$$

from which we see that the ratio of the equilibrium markups in the two sectors drives a wedge between the actual relative price and its counterpart in the competitive equilibrium, the inverse of the IST factor.

The question then becomes, under what circumstances do equilibrium markups in the two sectors coincide? We now show that the answer is never, even if we assume that the form and degree of nominal rigidity in the two sectors are the same. This demonstration follows along the lines of Proposition 3 in Benigno (2004). He shows that the efficient flexible price outcome is not feasible in a two-region economy with nominal rigidities in both. Here, we substitute two sectors to the two regions, and consider a more general production structure, but the essence of the argument remains the same.

Assume that prices are sticky in both sectors, according to the same time-dependent scheme described in the main text, with common parameter ξ_p, but with no indexation. The log-linearized Phillips curves are then

$$\hat{\pi}_{Ct} = \beta E_t\hat{\pi}_{Ct+1} + \kappa\hat{s}_{Ct} + \kappa\hat{\lambda}_{pt},$$

$$\hat{\pi}_{It} = \beta E_t\hat{\pi}_{It+1} + \kappa\hat{s}_{It} + \kappa\hat{\lambda}_{pt}$$

with $\kappa \equiv \frac{(1-\xi_p\beta)(1-\xi_p)}{\xi_p}$. Taking first differences, and using Eq. (A.2), we obtain

$$\hat{\pi}_{It} - \hat{\pi}_{Ct} = \beta E_t(\hat{\pi}_{It+1} - \hat{\pi}_{Ct+1}) + \kappa(\hat{s}_{It} - \hat{s}_{Ct}). \tag{A.3}$$

This equation, together with Eq. (A.2), allows us to prove the following proposition.

Proposition 1. *An equilibrium of the two-sector economy described above, in which* $P_{It}/P_{Ct} = \Upsilon_t^{-1}\ \forall t = 1,\ldots,\infty$, *is not feasible when prices are sticky in both sectors.*

Proof. If $P_{It}/P_{Ct} = \Upsilon_t^{-1}\ \forall t = 1,\ldots,\infty$, then A.2 implies $s_{Ct} = s_{It}\ \forall t = 1,\ldots,\infty$. From Eq. (A.3), this implies $\hat{\pi}_{It} - \hat{\pi}_{Ct} = 0$ $\forall t = 1,\ldots,\infty$, or $P_{It}/P_{Ct} = P_{I0}/P_{C0}\ \forall t = 1,\ldots,\infty$. A contradiction. □

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