BUSINESS CYCLES, INVESTMENT SHOCKS, AND THE "BARRO-KING" CURSE

Guido Ascari
Louis Phaneuf
Eric Sims

Business Cycles, Investment Shocks, and the "Barro-King" Curse
Guido Ascari, Louis Phaneuf, and Eric Sims
NBER Working Paper No. 22941
December 2016
JEL No. E31,E32

ABSTRACT

Recent empirical evidence identifies investment shocks as key driving forces behind business cycle fluctuations. However, existing New Keynesian models emphasizing these shocks counterfactually imply a negative unconditional correlation between consumption growth and investment growth, a weak positive unconditional correlation between consumption growth and output growth and anomalous profiles of cross-correlations involving consumption growth. These anomalies arise because of a short-run contractionary effect a positive investment shock on consumption. Such counterfactual co-movements are typical of the "Barro-King curse" (Barro and King 1984), wherein models with a real business cycle core must rely on technology shocks to account for the observed co-movement among output, consumption, investment, and hours. We show that two realistic additions to an otherwise standard medium scale New Keynesian model – namely, roundabout production and real per capita output growth stemming from trend growth in neutral and investment-specific technologies – can break the Barro-King curse and provide a more accurate account of unconditional business cycle comovements more generally. These two features substantially magnify the effects of neutral technology and investment shocks on aggregate fluctuations and generate a rise of consumption on impact of a positive investment shock.

Guido Ascari
Department of Economics
University of Oxford
Manor Road
Oxford OX1 3UQ
United Kingdom
guido.ascari@economics.ox.ac.uk

Louis Phaneuf
Department of Economics
University of Quebec at Montreal
320 Ste Catherine east
DS-5975
Montreal
Canada H3C 3P8
phaneuf.louis@uqam.ca

Eric Sims
Department of Economics
University of Notre Dame
723 Flanner Hall
South Bend, IN 46556
and NBER
esims1@nd.edu

1 Introduction

A recent literature identifies an *investment shock* as a key disturbance driving business cycle fluctuations. Fisher (2006) provides VAR-based evidence showing that investment shocks account for the bulk of cyclical fluctuations in hours and output. Justiniano and Primiceri (2008) and Justiniano, Primiceri, and Tambalotti (2010, 2011) reach a similar conclusion from estimation of a "medium-scale" New Keynesian model via Bayesian techniques. However, when investment shocks are the leading source of fluctuations, these models predict a negative unconditional correlation between consumption growth and investment growth, as well as a positive but weak unconditional correlation between consumption growth and output growth. In U.S. postwar data, the correlation between consumption growth and investment growth is positive and consumption growth is strongly procyclical.

Such anomalous comovements are symptomatic of what we refer to as the "Barro-King curse." In an influential paper, Barro and King (1984) conjecture that shocks other than those to total factor productivity (TFP) will have difficulty generating the business cycle comovements between output, consumption, investment, and hours found in the data. To illustrate the crux of their argument, let us consider how macroeconomic variables respond to an investment shock in a standard neoclassical framework. A positive shock to the marginal productivity of investment increases the rate of return on capital, giving households the incentive to save (invest) more in the present and postpone consumption for the future. Consumption hence declines after the shock. In turn, lower consumption increases the marginal utility of income, therefore shifting labor supply to the right along a fixed labor demand schedule. Hours and output rise, while the real wage and labor productivity fall. As a result, the investment shock triggers an investment boom accompanied by a short-run fall in consumption. To the extent to which the key disturbance driving business cycle fluctuations is the investment shock, the unconditional correlation between consumption and investment implied by the model will be negative. The model will also imply anomalous comovements between consumption and hours.

Models building off the neoclassical benchmark but including nominal rigidities and other sources of real inertia need not necessarily imply counterfactual comovement between consumption and other aggregate variables conditional on non-productivity shocks. That said, since the core of such models is the neoclassical benchmark studied by Barro and King (1984), their intuition is potentially still valid. It thus remains an open question whether or not non-technology shocks can generate strong unconditional comovement and if they do, under what conditions.

Our paper makes two contributions. First, we uncover significant business cycle anomalies affecting the recent class of "medium-scale" New Keynesian models driven by investment shocks – models which build off of the neoclassical core but include nominal and real rigidities – and identify the main factors causing them. Second, we show that two realistic additions to the otherwise standard medium-scale New Keynesian model remove the Barro-King curse. A first addition is that firms use intermediate goods as an input in production, in a so-called "roundabout production" structure (e.g., Basu, 1995; Huang, Liu, and Phaneuf, 2004), recently referred to as "firms networking" (e.g., Christiano, 2015). Evidence supporting this structure is discussed in Basu (1995), Huang, Liu, and Phaneuf (2004) and Nakamura and Steinsson (2010). It is also confirmed by a recent dataset gathered through the joints efforts of the NBER and the U.S. Census Bureau's CES covering 473 six-digit 1997 NAICS industries for the years 1959-2009. A second addition is that the economy realistically experiences real per capita output growth. Here, we model economic growth as resulting from trend growth in investment-specific and neutral technologies. Both additions to the standard medium-scale New Keynesian model form the basis of our benchmark model.

In the model we analyze throughout the paper, an investment shock is modeled as a shock to the marginal efficiency of investment (MEI) following Justiniano, Primiceri, and Tambalotti (2011). A MEI shock is one affecting the transformation of savings into future capital input, as opposed to an investment-specific technology shock affecting the transformation of consumption into investment goods identified with the relative price of investment.

With the MEI shock explaining the largest fraction of business cycle fluctuations, i.e. from 50 to 60 percent of output fluctuations, we find anomalies in the standard model (without firms networking and trend growth) related both to the *contemporaneous* correlation between consumption growth and investment growth and to the *patterns* of cross-correlations between these variables. The unconditional contemporaneous correlation between the growth rates of consumption and investment in the data is positive at 0.44. Meanwhile, the profiles of the cross-correlations between consumption growth and investment growth are substantially positive and decreasing both at lags and leads. The standard model faces the following two difficulties. First, it implies a negative unconditional contemporaneous correlation between consumption growth and investment growth. Second, the unconditional theoretical profiles of the cross-correlations between consumption growth and investment growth are more or less flat around zero instead of positive and decreasing. A key factor behind these anomalies is that consumption falls for more than a year following a positive MEI shock.

A second anomaly pertains to the the cross-correlations between consumption growth and the level of hours. The standard model matches the contemporaneous correlation between consumption

growth and the level of hours which is weakly positive in the data. However, it fails to replicate the profiles of cross-correlations between these variables.

A third significant anomaly relates to the correlations between consumption growth and output growth. In the data, the contemporaneous correlation between these variables is 0.75, while the cross-correlations are very positive and declining. We find that when the MEI shock explains the largest fraction of output fluctuations, the standard model predicts that the unconditional contemporaneous correlation between consumption growth and output growth will range from 0.39 to 0.26. Furthermore, the standard model systematically understates the cross-correlations between consumption growth and output growth found in the data.

When augmenting the model to include firms networking and trend output growth, we find that the New Keynesian model escapes the "Barro-King curse" in that our benchmark model predicts business cycle volatility and comovement statistics that are broadly consistent with the data when the MEI shock is the key disturbance. With the MEI shock acting as the key disturbance, our benchmark model predicts that the growth rates of output, consumption and investment comove positively. The unconditional correlation between consumption growth and investment growth turns positive, between 0.36 and 0.3 for a percentage contribution of the MEI shock to output fluctuations between 50 and 60 percent. Meanwhile, the unconditional correlation between consumption growth and output growth rises significantly, ranging from 0.7 to 0.66. Our model matches very well all the cross-correlograms and therefore significantly outperforms the standard New Keynesian model along this dimension. In particular, it significantly improves the cross-correlograms for consumption growth. The unconditional volatilities for consumption, investment and in hours implied by our model are close to those in the data.

What explains these findings? The marginal efficiency of investment shock could be thought as a demand shock whereby investment increases. Firms networking flattens the New Keynesian Phillips curve, making marginal costs less responsive and the boom more long-lasting. Moreover, trend growth also contributes to a lower response to inflation because price-setters are more forward-looking and less sensitive to current conditions. As a consequence, an investment shock has a bigger and more prolonged effect on output, generating a stronger income effect in our model. A Hicksian decomposition as in King (1991) shows that the income effect in a model with firms networking and growth is twice as strong as the one in a model without those features. Such a strong income effect is able to overturn the negative substitution effect on consumption, so that the initial response of consumption is positive.

The existing literature shows that firms networking can amplify the real effects of monetary policy shocks (Basu, 1995; Bergin and Feenstra, 2000; Huang, Liu, and Phaneuf, 2004; Nakamura

and Steinsson, 2010). But little work has been done to study the magnifying effect of firms networking for other types of shocks, despite estimations of New Keynesian models in the literature showing that monetary policy shocks account for only a very small fraction of fluctuations in output, consumption, investment, and hours worked (i.e., less than 5 percent, according to estimates in Justiniano, Primiceri, and Tambalotti, 2011). Accounting for firms networking can be particularly important when a MEI shock explains the largest fraction of output fluctuations. A first effect of firms networking is to increase the wedge between the marginal product of labor (MPL) and the marginal rate of substitution between consumption and leisure (MRS), allowing the MEI shock to have a bigger impact on output and hence consumption to rise. A second effect is that a change in intermediate inputs following a MEI shock shifts the MPL schedule for a given level of hours.

Relation to the literature. We are not the first to try to overcome these anomalies. A number of authors have used non-standard preferences imposing restrictions on labor-supply decisions. Greenwood, Hercowitz, and Huffman (1988) assume preferences implying that labor supply decisions are independent of the intertemporal consumption-savings choice. Jaimovich and Rebelo (2009) use preferences allowing for a weak wealth effect on labor supply in order to fix some business cycle comovements in both a one and a two-sector neoclassical growth model. Eusepi and Preston (2015) features a labor market with both an extensive and an intensive margin together with the assumption of complementarity between consumption and hours worked. These two features are meant to capture the empirical evidence that households' substitute market and non-market work over the business cycle and that employed households consume more than unemployed households. It follows that an increase in hours after a MEI shock leads to an increase in the number of employed households and thus an increase in aggregate consumption.

A different approach, perhaps closer to ours, maintains standard (i.e. time-separable) preferences in the so-called "medium-scale" New Keynesian model with investment shocks (e.g., Christiano, Eichenbaum, and Evans, 2005; Smets and Wouters, 2007; Altig et al., 2011; Justiniano, Primiceri, and Tambalotti, 2010, 2011). Following Christiano, Eichenbaum, and Evans (2005), the term "medium-scale" refers to a class of models that includes imperfectly competitive goods and labor markets, sticky wages and sticky prices, as well as real frictions like habit formation in consumption, variable capital utilization and investment adjustment costs. Imperfect competition in the labor and goods markets drives a wedge between the MPL and the MRS. With sticky wages and prices, this wedge is endogenous and can vary over the business cycle. This wedge is a fundamental mechanism for the transmission of shocks that breaks down the intratemporal efficiency condition. As a result, the MRS does not strictly equal the MPL, so the relative movements of consumption and hours are not as tightly constrained as in a perfectly competitive economy. Accounting for

investment shocks, the breakdown of the intratemporal efficiency condition is not sufficient to break the Barro-King curse in existing New Keynesian models for standard calibration values. As we show in the paper, only by assuming implausibly large values of the degree of price stickiness and wage stickiness it is possible to generate a positive impact response of consumption to an investment shock.

The paper which is perhaps closest to ours is the one by Furlanetto and Seneca (2014). However, our approach is quite different from theirs. Furlanetto and Seneca (2014) use a DSGE model that combines sticky prices, a form of preferences implying an Edgeworth complementarity between consumption and hours, investment adjustment costs and a single shock to the marginal efficiency of investment. They argue that the Edgeworth complementarity is important in generating a positive comovement between consumption and hours and an increase in consumption at the onset of a positive shock to the marginal efficiency of investment. By contrast, our model is more general and features standard preferences, sticky wages and sticky prices, positive trend inflation, consumer habit formation, variable capital utilization, investment adjustment costs, networks, economic growth, and shocks to the marginal efficiency of investment (MEI), neutral technology (TFP), monetary policy and intertemporal preference. Furthermore, while Furlanetto and Seneca focus primarily on the impulse-responses of consumption and hours to an investment shock, we look at impulse responses *and* volatilities and various comovement business cycle statistics implied by alternative models.

The remainder of the paper is organized as follows. Section 2 lays out our medium-scale DSGE model. Section 3 discusses some issues related to calibration. Section 4 mesaures how the standard medium-scale New Keynesian model squares with the Barro-King curse compared to our model which adds firms networking and trend output growth. Section 5 contains concluding remarks.

2 Model and Calibration

2.1 The Model

Our medium-scale New Keynesian model embeds a number of features of other similar models in the literature, namely standard preferences, nominal rigidities in the form of Calvo (1983) wage and price contracts, habit formation in consumption, investment adjustment costs, variable capital utilization and a Taylor rule. The Appendix A lays out the model equations in detail. Here we focus on two features of our model that are important for our results: firms networking and output growth.

The first feature we add, relative to standard models (e.g., Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007)) is the use of intermediate inputs or firms networking (hereafter, FN). FN is added to our model through the use of intermediate inputs, $\Gamma_t(j)$, as an input in the production function for a typical producer j, that is given by:

$$X_t(j) = \max \left\{ A_t \Gamma_t(j)^\phi \left(\widehat{K}_t(j)^\alpha L_t(j)^{1-\alpha} \right)^{1-\phi} - \Upsilon_t F, 0 \right\}, \tag{1}$$

where A_t is neutral productivity, F is a fixed cost, Υ_t is a growth factor (see below) and production is required to be non-negative, and $\phi \in (0,1)$ is the intermediate input share. Intermediate inputs come from aggregate gross output, X_t. $\widehat{K}_t(j)$ is capital services or the product of utilization and physical capital, while $L_t(j)$ is labor input. The cost minimization problem of a typical firm yields the following expression for real marginal cost, v_t, which is common across firms:

$$v_t = \overline{\phi} A_t^{-1} \left(r_t^k \right)^{\alpha(1-\phi)} w_t^{(1-\alpha)(1-\phi)}, \tag{2}$$

where $\overline{\phi}$ is a constant, r_t^k is the common real rental price on capital services (the product of utilization and physical capital) and w_t is the real wage index. This expression for real marginal cost shows that relative to the basic case in the literature, FN reduces the sensitivity of real marginal cost to factor prices by a factor of $1 - \phi$. Hence, FN flattens the New Keynesian Phillips Curve, amplifying the stickiness in the economy caused by nominal rigidities.

The second important feature of our model is real per capita output growth stemming from two distinct sources: trend growth in neutral technology and in investment-specific technology (IST). Greenwood, Hercowitz, and Krusell (1997) show that investment-specific technological change has been a major source of U.S. economic growth during the postwar period. In the context of our model, trend growth in IST realistically captures the downward secular movement in the relative price of investment observed during the postwar period. First, neutral productivity obeys a process with both a trending and stationary component.

$$A_t = A_t^\tau \widetilde{A}_t, \tag{3}$$

A_t^τ is the deterministic trend component that grows at a constant gross rate g_A, while $\widetilde{A}_t$ is the stationary component. The initial level in period 0 is normalized to 1: $A_0^\tau = 1$. The stationary component follows an AR(1) process. To introduce IST, we specify the physical capital accumulation process as follows:

$$K_{t+1} = \varepsilon_t^{I,\tau} \vartheta_t \left(1 - S \left(\frac{I_t}{I_{t-1}} \right) \right) I_t + (1 - \delta) K_t, \tag{4}$$

where K_t is the physical capital stock and I_t is investment measured in units of consumption. $S\left(\frac{I_t}{I_{t-1}}\right)$ is an investment adjustment cost that satisfies $S\left(g_I\right) = 0$, $S'\left(g_I\right) = 0$, and $S''\left(g_I\right) > 0$, where $g_I \geq 1$ is the steady state (gross) growth rate of investment. $0 < \delta < 1$ is the depreciation rate. $\varepsilon_t^{I,\tau}$ measures the level of IST and it enters the capital accumulation equation by multiplying investment.[1] $\varepsilon_t^{I,\tau}$ follows a deterministic trend with no stochastic component, where $g_{\varepsilon I}$ is the gross growth rate. ϑ_t is a shock to the marginal efficiency of investment.

Most variables in the model inherit trend growth from the deterministic trends in neutral and investment-specific productivity.[2] Suppose that this trend factor is Υ_t. Output, consumption, investment (measured in units of consumption), intermediate inputs, and the real wage all grow at the rate of this trend factor on a balanced growth path: $g_Y = g_I = g_\Gamma = g_w = g_\Upsilon$. The capital stock grows faster due to growth in investment-specific productivity, with $\widetilde{K}_t \equiv \frac{K_t}{\Upsilon_t \varepsilon_t^{I,\tau}}$ being stationary. The trend factor inducing stationarity among transformed variables is:

$$\Upsilon_t = (A_t^\tau)^{\frac{1}{(1-\phi)(1-\alpha)}} \left(\varepsilon_t^{I,\tau}\right)^{\frac{\alpha}{1-\alpha}}. \tag{5}$$

Note the interaction between FN and growth in this expression. When there are no intermediate inputs, this expression reverts to the conventional trend growth factor in a model with growth in neutral and investment-specific productivity. (5 implies that a higher value of the share of intermediate inputs ϕ amplifies the effects of trend growth in neutral productivity on output and its components. For a given level of trend growth in neutral productivity, the economy will grow faster the larger is the share of intermediates in production.

ϑ_t in (4) is a stochastic MEI shock. Justiniano, Primiceri, and Tambalotti (2011) distinguish between IST and MEI, showing that IST growth maps one-to-one into the relative price of investment goods, while MEI shocks have no impact on the relative price of investment. Their evidence suggests that the MEI shock is the main disturbance explaining business cycle fluctuations, while the stochastic shock to IST virtually has no impact on output at business cycle frequencies. This explains why in our model the MEI component is stochastic while the IST term affects trend growth only.

Our model includes four shocks: MEI, neutral productivity, intertemporal preference and monetary policy. In Christiano, Eichenbaum, and Evans (2005), aggregate fluctuations are driven solely by monetary policy shocks. In Smets and Wouters (2007) they are driven by seven shocks. Chari, Kehoe, and McGrattan (2009), however, criticize multi-shock New Keynesian models, arguing that

---

[1] $\varepsilon_t^{I,\tau}$ also enters the budget constraint in terms of the resource cost of capital utilization, see Appendix A.2.

[2] Given our specification of preferences, labor hours are stationary.

of the several shocks used in these models, only three can be viewed as truly "structural" in the sense of having a clear economic interpretation: investment, neutral technology, and monetary policy. So, we keep these three shocks in the model. We also keep the intertemporal preference shock since Justiniano, Primiceri, and Tambalotti (2011) find that this shock explains less than 6 percent of fluctuations in output, investment, and hours, but 55 percent of consumption fluctuations. The MEI shock follows a stationary AR(1) process, with innovation u_t^I drawn from a mean zero normal distribution with standard deviation s_I:

$$\vartheta_t = (\vartheta_{t-1})^{\rho_I} \exp(s_I u_t^I), \quad 0 \le \rho_I < 1 \tag{6}$$

The stationary component of neutral productivity, $\widetilde{A}_t$, follows an AR(1) process in the log, with the non-stochastic mean level normalized to unity, and innovation, u_t^A, drawn from a mean zero normal distribution with known standard deviation equal to s_A:

$$\widetilde{A}_t = \left(\widetilde{A}_{t-1}\right)^{\rho_A} \exp\left(s_A u_t^A\right), \quad 0 \le \rho_A < 1, \tag{7}$$

The intertemporal preference shock ε_t^b follows a stationary AR(1) process:

$$\varepsilon_t^b = (\varepsilon_{t-1}^b)^{\rho_b} \exp(s_b u_t^b), \tag{8}$$

with innovation u_t^b drawn from a mean zero normal distribution with standard deviation s_b. The monetary policy shock represents a random deviation from the following Taylor rule:

$$\frac{1+i_t}{1+i} = \left(\frac{1+i_{t-1}}{1+i}\right)^{\rho_i} \left[\left(\frac{\pi_t}{\pi}\right)^{\alpha_\pi} \left(\frac{Y_t}{Y_{t-1}} g_Y^{-1}\right)^{\alpha_y}\right]^{1-\rho_i} \varepsilon_t^r. \tag{9}$$

According to this specification, the central bank adjusts the nominal interest rate, i_t, in response to deviations of current inflation, π_t, from an exogenous steady-state inflation target, π, and to deviations of output growth from its steady-state level, g_Y. ε_t^r is the exogenous shock to the policy rule and it is assumed to be white noise. ρ_i is a smoothing parameter while α_π and α_y are two policy parameters. We restrict attention to parameter configurations giving rise to a determinate equilibrium.

It is worth mentioning that our model omits wage and price indexation either to past or steady-state inflation. Combined with Calvo contracts, either form of indexation implies that all nominal wages and prices change every quarter. This is inconsistent with evidence that many wages and prices remain fixed for relatively long periods of time (e.g., Eichenbaum, Jaimovich, and Rebelo,

2011; Klenow and Malin, 2011; Barattieri, Basu, and Gottschalk, 2014). Indexation is also criticized for a lack of microeconomic foundations (Chari, Kehoe, and McGrattan, 2009). Moreover, Cogley and Sbordone (2008) find no evidence of price indexation to the previous period's rate of inflation when combining sticky prices with time-varying trend inflation. Therefore, indexation has been omitted from the late New Keynesian models of Christiano, Trabandt, and Walentin (2010), Christiano, Eichenbaum, and Trabandt (2015, 2016), Ascari, Phaneuf, and Sims (2015) and Phaneuf, Sims, and Victor (2015). As in these models, the presence of FN is able to generate realistic inertia in inflation, without the unrealistic assumption of backward-looking indexation.

Appendix A contains a detailed description of the model together with the full set of equilibrium conditions re-written in stationary terms.

2.2 Calibration

Tables 1 and 2 summarize the calibration of the model, which is rather standard and in line with the literature (e.g., Christiano, Eichenbaum, and Evans, 2005; Justiniano, Primiceri, and Tambalotti, 2010, 2011). Appendix B discusses it in details. Here, we again focus on the central ingredients of our model: FN, trend growth, and the shocks.

The share of intermediate inputs, ϕ, is set to 0.61. The values of ϕ used in the comparable literature typically range from 0.5 to 0.8. Ours is obtained as follows. Following Nakamura and Steinsson (2010), we take the weighted average revenue share of intermediate inputs in the U.S. private sector using Consumer Price Index (CPI) expenditure weights to be roughly 51 percent in 2002. The cost share of intermediate inputs is equal to the revenue share times the price markup. Since our calibration implies a markup of 1.2, our estimate of the weighted average cost share of intermediate inputs is roughly 0.61.

Mapping the model to the data, the trend growth rate of the IST term, g_{ε^I}, equals the negative of the growth rate of the relative price of investment goods. To measure this in the data, we define investment as expenditures on new durables plus private fixed investment, and consumption as consumer expenditures of nondurables and services. These series are from the BEA and cover the period 1960:I-2007:III, to leave out the financial crisis.[3] The relative price of investment is the ratio of the implied price index for investment goods to the price index for consumption goods. The average growth rate of the relative price from the period 1960:I-2007:III is -0.00472, so that $g_{\varepsilon^I} =$ 1.00472. Real per capita GDP is computed by subtracting the log civilian non-institutionalized population from the log-level of real GDP. The average growth rate of the resulting output per capita series over the period is 0.005712, so that $g_Y = 1.005712$ or 2.28 percent a year. Given the

---

[3]A detailed explanation of how these data are constructed can be found in Ascari, Phaneuf, and Sims (2015).

calibrated growth of IST, we then use (5) to set $g_A^{1-\phi}$ to generate the appropriate average growth rate of output. This implies $g_A^{1-\phi} = 1.0022$ or a measured growth rate of TFP of about 1 percent per year.[4]

Regarding the calibration of the shocks, we set the autoregressive parameter of the neutral productivity shock at 0.95. Based on the estimate in Justiniano, Primiceri, and Tambalotti (2011), we set the baseline value of the autoregressive parameter of the MEI process at 0.8 and that of the intertemporal preference shock at 0.6. In the robustness Section 4, we also look at the effects of increasing the persistence of the MEI shock to 0.95.

Our procedure to pin down the standard deviations of the four shocks in our model is to target the size of shocks s_A, s_I, s_b and s_r, for which the model exactly matches the actual standard deviation of output growth observed in our data (0.0078). In doing that, we also take into account that the average growth rate of the price index over the period 1960:I-2007:III is 0.008675. This implies a positive steady-state inflation of 3.52 percent annualized ($\pi^* = 1.0088$).[5] We then assign to each shock a target percentage contribution to the unconditional variance decomposition of output growth. Our targets for the contribution of the shocks to the variance of output growth are based on empirical consensus from the recent literature. In this literature, investment shocks are the main driver behind business-cycle fluctuations, followed by neutral technology shocks. In the estimates from Justiniano, Primiceri, and Tambalotti (2010), the investment shock explains about 50 percent of the variance decomposition of output growth at business cycle frequencies, followed by the neutral technology shock with 25 percent, the intertemporal preference shock with 7 percent and the monetary policy shock with 5 percent. This leaves only 13 percent to be explained by other types of shocks which in their model are government-spending, price-markup, and wage-markup shocks. Justiniano, Primiceri, and Tambalotti (2011) distinguish between an investment-specific technology (IST) shock and a shock to the marginal efficiency of investment (MEI). The MEI shock explains 60 percent of fluctuations in output growth, the neutral technology 25 percent, the intertemporal preference shock 5 percent and the monetary policy shock 4 percent. This leaves only 6 percent of output fluctuations to be explained by other types of shocks. Other studies in which investment shocks explain a larger fraction of output fluctuations than TFP shocks include Fisher (2006), Justiniano and Primiceri (2008) and Altig et al. (2011).[6]

---

[4]Note that this is a lower average growth rate of TFP than would obtain under traditional growth accounting exercises. This is due to the fact that our model includes FN, which would mean that a traditional growth accounting exercise ought to overstate the growth rate of true TFP.

[5] Ascari, Phaneuf, and Sims (2015) study the welfare and cyclical implications of moderate trend inflation.

[6]One exception, however, is Smets and Wouters (2007), who report that investment shocks account for less than 25 percent of the forecast error variance of GDP at any horizon. Justiniano, Primiceri, and Tambalotti (2010) explore the reasons for these differences, showing that the smaller contribution of investment shocks in Smets and Wouters (2007) results from their definition of consumption and investment which includes durable expenditures in

To determine the exact numerical values for s_A, s_I, s_b and s_r, our baseline calibration assigns 50 percent of the variance of output growth to the MEI shock, 35 percent to the TFP shock, 8 percent to the intertemporal preference shock, and 7 percent to the monetary policy shock. The MEI shock is thus the key disturbance driving the business cycle, but the TFP shock remains quite important. Table 3 displays the values of the standard deviations of the shocks generated through this procedure for four different versions of our model. The first column refers to a model with no FN and no growth, that we name for simplicity "standard New Keynesian model" in the text. The second column refers to our benchmark model with FN and growth. The last two columns refer to versions of the model where one of the two additional features is switched off.

What is striking about these numbers is that, with intermediate inputs and trend output growth, the standard deviations of the TFP and MEI shocks needed to match the actual volatility of output growth are much smaller. The neutral technology shock is nearly 61 percent smaller with these features added to the model. FN is the key factor behind the magnifying effects of a neutral technology shock. With only FN added to the model, the neutral technology shock is nearly 58 percent smaller. This is not surprising since relative to the standard model, the productivity shock in essence affects output "twice" with roundabout production, first via its direct effect on output in the production function and then indirectly through its effect on intermediate inputs. The standard deviation of the MEI shock is 32 percent smaller than in the standard model, and both FN and growth contribute to this reduction in roughly equal proportions. The model with FN and trend growth also magnifies the effects of monetary policy shocks on output, with a standard deviation of the shock which is 21 percent smaller than in the standard model. FN and growth have comparably little effect on the standard deviation of the intertemporal preference shock in our calibration exercise.[7]

3 Removing the Barro-King Curse

3.1 Business Cycle Moments

This section addresses the following two questions. Is the standard medium-scale New Keynesian model subject to the Barro-King curse when the most important type of disturbance driving the business cycle in the model is an investment shock? If the answer is affirmative, is it possible to

consumption while excluding the change in inventories from investment, although not from output. With the more standard definition of consumption and investment found in the business-cycle literature (e.g., Cooley and Prescott, 1995; Christiano, Eichenbaum, and Evans, 2005; Del Negro et al., 2007), they find that investment shocks explain more than 50 percent of business-cycle fluctuations.

[7]In the robustness Section 4, we also consider two other different splits for the target contribution of shocks to the unconditional variance decomposition of output growth.

remove the curse by adding plausible theoretical ingredients to the standard model? To answer the first question, we show that the standard model (i.e. abstracting from roundabout production and trend output growth) is indeed subject to anomalous comovements which are described below. Then, we show that these anomalies can be removed when adding intermediate inputs and real per capita output growth to the standard model.

We focus on moments that help us assessing the severity of the Barro-King curse in the standard model. We first look at volatility and comovement business cycle statistics. The sample period is 1960:Q2-2007:Q3. The statistics involve the growth rates of output, consumption and investment. While we report the volatility of the growth rate in hours, when it comes to correlations, we report comovements between the level of hours and the growth rates of output and consumption, because in our model hours worked are stationary in levels.

The first row in Table 4 displays these moments in the data. Consumption growth is 40 percent less volatile than output growth. Investment growth is 2.6 times more volatile than output growth. First-differenced hours are about as volatile as output growth. These relative volatilities are well known stylized facts in the business cycle literature. The correlation between investment growth and output growth is positive and high at 0.92. Consumption growth is also quite procyclical, but less than investment growth, with a correlation of 0.75. The correlation between the growth rates of consumption and investment is positive and mild in the data at 0.44. The correlation between output growth and hours in levels is weakly positive at 0.11, and so is the correlation between consumption growth and the level of hours at 0.075.

Figure 1 displays the cross-correlograms between key macroeconomic variables. The cross-correlations in the data are represented by the lines with circles. The cross-correlograms (dY_t, dC_{t-k}) and (dC_t, dY_{t-k}), $k = 0, .., 4$, are positive and decreasing in the data. The same is true for (dY_t, dI_{t-k}) and (dI_t, dY_{t-k}), but with a contemporaneous correlation between output growth and investment growth which is somewhat higher than for consumption growth and output growth. Two of the cross-correlograms that will be the object of a particular attention are those between consumption growth and investment growth, (dC_{t-k}, dI_t) and (dC_t, dI_{t-k}). In both cases, these cross-correlations are substantially positive and decreasing in the data. Two other profiles of cross-correlations that are worth mentioning are those for (dC_t, L_{t-k}) and (dC_{t-k}, L_t). The contemporaneous correlation between consumption growth and the level of hours is slightly positive in the data, while the cross-correlations (dC_t, L_{t-k}), $k = 1, ..4$, are mildly decreasing and those for (L_t, dC_{t-k}) are positive and increasing.

3.2 Identifying the Anomalies in the Standard Medium-Scale New Keynesian Model

The second row of Table 4 reports business cycle statistics from the standard medium-scale New Keynesian model (i.e., No FN/No G).[8] We first look at volatility statistics. The model exactly matches the volatility of output growth in the data by construction. It does reasonably well reproducing other volatility statistics. The model nearly matches the volatility of consumption growth in the data. However, it overstates the volatility of investment growth by 23 percent, and the one of hours growth by 25 percent.

Most importantly, the standard model fails along the following dimensions as foreseen by Barro and King (1984). A first significant anomaly concerns the unconditional correlation between the growth rates of consumption and investment. The correlation implied by the model is weakly negative (-0.05) compared to quite positive in the data (0.44). Furthermore, the cross-correlations between consumption and investment for both (dC_{t-k}, dI_t) and (dC_t, dI_{t-k}) implied by the standard model and denoted by the solid lines in Figure 1 are more or less flat around zero, in contrast to substantially positive and decreasing in the data.

The second anomaly is that the unconditional correlation between consumption growth and output growth is weakly positive in the model (0.39) as opposed to strongly positive in the data (0.75). Furthermore, the cross-correlations between consumption growth and output growth are always lower in the standard model than in the data, not only for the contemporaneous one (as we know from Table 4). As we later show, these two anomalies get even more severe the more persistent the MEI shock is. The standard model however predicts that investment growth is highly procyclical unconditionally, which is consistent with the data.

A third anomaly has to do with the cross-correlations between consumption growth and the level of hours. While the contemporaneous unconditional correlation between consumption growth and the level of hours is somewhat understated by the standard model, it is not too far from the low and positive value observed in the data. The problem is with the profile of cross-correlations between these variables. That is, (dC_t, L_{t-k}) is increasing in the model and relatively flat (mildly decreasing) in the data, while (dC_{t-k}, L_t) is increasing in the model but much less than in the data.

The main anomalies of the standard model we have identified so far all relate to consumption. What are the reasons for these inconsistencies found in the standard medium-scale New Keynesian model? The main factor is a negative short-run response of consumption that follows a positive MEI shock, as shown by the dotted line in the second panel of the first row of Figure 2. The MEI

---

[8]When comparing moments predicted by alternative models to the data, the models are solved via second order perturbation about the non-stochastic steady state.

shock can be seen as an aggregate demand shock that raises the current demand for (investment) goods relative to supply, pushing output and inflation in the same direction. Moreover, following a positive MEI shock, investment is more profitable, so agents substitute consumption for investment. The impulse response function is hump-shaped, so consumption drops on impact, keeps decreasing for two quarters, and then starts increasing turning above steady state after 6 quarters. A more persistent MEI shock just makes things worse and the anomalies more severe.

3.3 Overcoming Business Cycle Anomalies: Adding Firms Networking and Economic Growth

Here, we examine how the addition of firms networking and economic growth impacts unconditional moments vis-à-vis the standard model. The unconditional moments from our model are shown in Table 4. The unconditional correlation between the growth rates of consumption and investment is now positive and close to the correlation observed in the data (0.36 in the model vs. 0.44 in the data). The unconditional correlation between consumption growth and output growth also improves substantially, being equal to 0.70 in the model compared to 0.75 in the data. The unconditional correlation between investment growth and output growth implied by the FN/G model is nearly 0.9, as found in the data. With respect to hours, our model does as well as the standard model, with the unconditional correlation between output growth and the level of hours marginally worsening, while the one between consumption growth and hours marginally improves. Finally, Table 4 shows that our benchmark model with firms networking and trend output growth almost exactly matches the volatilities of consumption growth, investment growth, and the log first difference in hours worked which also represents an improvement over the standard model.

Another dimension along which our benchmark model improves over the standard medium-scale New Keynesian is its ability to broadly reproduce the profiles of all the cross-correlograms which are denoted by the dashed lines in Figure 1. Note in particular how well it reproduces the positive and decreasing cross-correlations (dC_t, dI_{t-k}) compared to the pattern predicted by the standard model which is more or less flat around zero. As for the cross-correlations (dC_{t-k}, dI_t), the benchmark model also captures the positive and decreasing profile, marking an improvement over the standard model which, once again, implies a flat pattern around zero.

The benchmark model also closely matches the positive and decreasing cross-correlations between consumption growth and output growth, and this at leads and lags. It is also broadly consistent with the cross-correlations (dC_t, L_{t-k}) and (dC_{t-k}, L_t) found in the data, while the standard model performs less well along this particular dimension. All in all, the benchmark model

14

outperforms the standard New Keynesian model on almost all the cross-correlograms and its ability to reproduce all the cross-correlations is quite striking.

The key to these improved results is the short-run response of consumption after a positive MEI shock which is markedly different in the benchmark model with FN and trend output growth, as shown by the solid line in the second panel of the first row of Figure 2. Here, consumption rises on impact of a positive MEI shock and it increases over time.

But why does the response of consumption turn positive? Because of a stronger income effect. Figure 2 shows that the response of output is more persistent in our benchmark model. The output path is very close to the one of the standard model for the first two quarters, but our benchmark model creates a larger hump from period three and onward. Output keeps increasing in our model because the response of the marginal costs, and also of inflation, is more muted in presence of FN. The MEI shock is ultimately a demand shock whereby investment increases. FN flattens the Phillips curve, making marginal costs less responsive and the boom more long-lasting. Moreover, trend growth also contributes to a lower response to inflation because price-setters are more forward-looking and less sensitive to current conditions.

The higher path of output creates a stronger income effect in our model. This can be seen from Figure 3 where we use the Hicksian decomposition proposed by King (1991).[9] There, we can see that the income effect on consumption induced by the MEI shock in our model is twice the income effect in the standard model (6.9×10^{-4} vs. 3.4×10^{-4}). While the income effect generated by the standard New Keynesian model is too low to turn the response of consumption from negative (due to the substitution effect) to positive, the one generated by our benchmark model is able to overturn the negative substitution effect on consumption. The income effect on hours has the same absolute value and the opposite sign.[10] It follows that households consume more and work less. Hence, the response of investment is lower on impact, but more persistent in our model.

To conclude, a medium-scale model with FN and growth makes the key macroeconomic variables (i.e., output, consumption, investment and hours) positively comove after a MEI shock, which is not the case after a positive TFP shock since output, consumption and investment then increase while hours decline in the short run. As such, this model breaks the Barro-King's curse formulated in a neoclassical framework that only TFP shocks are able to generate the typical positive comovements between these variables. It actually goes further than just removing the Barro-King curse, because

---

[9]Following King (1991), we define the income effect as the change in consumption and hours that would yield the same level of intertemporal utility as the one generated by the shock, keeping the prices, wages and interest rate constant at the steady state levels.

[10]This is because preferences are time separable and the instantaneous utility when $\chi = 1$ implies unit elastic demand, as noted by King (1991).

it is able to reproduce business cycle moments between key macroeconomic variables beyond relative volatilities and contemporaneous correlations. As we have found, it also quite closely matches the cross-correlograms between the key macroeconomic variables (i.e., output, consumption, investment and hours) in the data.

3.4 Disentangling the effects of FN and Growth

Next, we disentangle the effect of roundabout production vs. trend output growth on our findings. Table 4 shows the comovements implied by the following two versions of the model: one with growth but no FN (No FN/ Growth) and the other with FN an no growth (FN/No Growth).[11] The Table shows that both trend output growth and FN lead to some improvements in business cycle comovements with respect to the standard model. For instance, the unconditional correlation between the growth rates of consumption and investment becomes positive when one of the two features is added to the model. However, it is much lower than in the data (0.123 or 0.19, respectively, vs. 0.44 in the data). This represents a step in the right direction but is not enough to overcome the anomaly. This also applies to the correlation between the growth rates of consumption and output.

Figure 2 highlights the relative role of these two features in breaking the Barro-King curse. Trend growth affects mainly the persistence of the IRFs of the variables to a MEI shock with respect to the standard model. In this case, the initial responses (see dashed lines) of output and hours are similar to the standard model, but the IRFs are more persistent. According to the previous intuition, trend growth makes price-setting more forward-looking and less sensitive to current conditions, thereby flattening the Phillips curve. Indeed, the response of inflation is slightly more muted. This generates a stronger wealth effect relative to the standard model, such that there is less substitution between consumption and investment: consumption decreases less and investment increase less with respect to the standard model. FN instead lowers the response of inflation to a MEI shock by making the response of marginal cost more muted. Hence, FN affects the initial response of output and other variables, rather than their persistence. As a result, the consumption response is higher initially with FN rather than with economic growth, but 6 quarters after the shock it is the opposite, because trend growth makes the IRFs more persistent.

So while FN and trend output growth each contributes in their own way to fix the anomalies of the standard medium-scale New Keynesian model, it is really the interaction between these two ingredients in the FN/G model that contributes to break the Barro-King curse within this class of models.

---

[11]Recall that for each version, we rescale the size of shocks so the model exactly matches that the volatility of output growth in the data, see Table 3.

Previously, we have argued that most of the action is due to a muted response of inflation. Hence, to further illustrate the usefulness of combining FN and economic growth to avoid the short-run decline in consumption following a positive MEI shock, we now ask what the Calvo probabilities of wage and price non-reoptimization would need to be in the standard New Keynesian model to generate the same increase in consumption on impact in response to a positive investment shock as in the FN/G model. Here, we consider three different scenarios. In the first scenario, the Calvo probability of wage non-reoptimization ξ_w is kept at 2/3, while we search for the appropriate Calvo probability of price non-reoptimization ξ_p. The second scenario is a similar exercise, except that this time we keep ξ_p at 2/3 while searching for ξ_w. Lastly, we set $\xi_w = 0.76$ following the microeconomic evidence found in Barattieri, Basu, and Gottschalk (2014) and search for ξ_p. [12]

The results are presented in Figure 4. Panel A of the Figure shows the results for the first scenario. Here we report the response of consumption with $\xi_p = 0.88$ and $\xi_w = 2/3$. [13] For $\xi_p = 0.88$, which represents an average waiting time between price adjustments of 25 months, we find that the increase in consumption is smaller on impact after a MEI shock and is also smaller at all horizons than in our benchmark model under our baseline calibration. Of course, having prices adjust once every 25 months on average is empirically implausible. Panel B shows the results corresponding to the second scenario. With ξ_p kept at 2/3, ξ_w would need to be 0.82 to match the rise in consumption on impact of a positive investment shock in the benchmark model. This represents an average frequency of nominal wage adjustment of once every 17 months, which is significantly higher than assumed in the benchmark model under our baseline calibration. Panel C sets ξ_w at 0.76, so ξ_p needs to be 0.86, meaning that prices adjust once every 21.5 months on average to match the initial rise in consumption in the benchmark model.

What do we conclude from these three exercises? We conclude that it takes implausibly high Calvo probabilities of wage and price non-reoptimization in the standard model to avoid the short-run decline in consumption following a positive investment shock.

4 Robustness

In this Section, we look at the robustness of our results with respect to: (i) the relative contributions of the shocks to the unconditional variance decomposition of output growth; (ii) the autoregressive coefficient of the MEI shock.

---

[12] As usual also for these exercises above, we rescale the size of shocks so that our model matches the postwar volatility of output growth.

[13] The model does not have a determinate solution for ξ_p higher than 0.88 because of a positive trend inflation rate of 3.52 annually (see Ascari and Ropele, 2009; Coibion and Gorodnichenko, 2011).

4.1 Relative Size of Shocks

Here we consider two other different splits of the relative importance of shocks in determining the variance of output growth. A first split (Split 1) increases the relative importance of MEI shocks, by setting the target contribution of the MEI shock and TFP shock to 60 and 25 percent, respectively. This split is broadly consistent with the evidence reported in Justiniano, Primiceri, and Tambalotti (2011) where the MEI shock is by far the most important disturbance driving business cycle fluctuations. A second split (Split 2) increases the importance of TFP shocks relative to our benchmark case, assigning 45 percent to the TFP shock and 40 percent to the MEI shock, so that the TFP shock becomes the main disturbance driving the business cycle. In both splits, the percentage contributions of the other two shocks are kept constant. The numerical values for the shocks standard deviation for these two splits for the alternative models are reported in Table 5. As expected, no matter what the split of shocks is, the standard deviation of the MEI shock is by far the largest, followed by the standard deviation of the intertemporal preference shock, then of the neutral technology shock, and last of the monetary policy shock.

Table 6 replicates Table 4 showing selected business cycle moments for the two splits. As expected from the Barro-King curse, the less important are the TFP shocks (or the more important are the MEI shocks), the farther away from the data are the contemporaneous correlations between consumption growth and investment growth and between consumption growth and output growth. However, when the percentage contribution of the neutral technology shock decreases from the 35 to 25 percent, these two unconditional comovements deteriorate more in the standard model (from -0.05 to -0.16 for $\rho(\Delta C, \Delta I)$ and from 0.39 to 0.26 for $\rho(\Delta Y, \Delta C)$) than in the benchmark model (from 0.36 to 0.30 for $\rho(\Delta C, \Delta I)$ and from 0.7 to 0.65 for $\rho(\Delta Y, \Delta C)$). In contrast, with a less important TFP shock, either model better replicates the contemporaneous correlations related to hours.

Whatever the split of the shocks: (i) the standard model remains far off in replicating two key correlations in the business cycle: the one between consumption growth and investment growth and the one between consumption growth and output growth; (ii) our benchmark model instead gets quite close in replicating the data. Moreover, similarly to Figure 1, Figure 5 shows the cross-correlograms for our benchmark calibration and for the two alternative splits. It demonstrates that the results from our model are quite robust to the changes in the relative importance of the shocks. Intuitively, the cross-correlograms from our benchmark calibration are between the ones generated from Split 1 and 2. The alternative splits have some effects on these cross-correlograms, but these effects are quite marginal.

4.2 Persistence of MEI shock

The results are sensitive to the degree of persistence of the MEI shock. Table 7 shows how selected business cycle moments change when ρ_I assumes a lower (0.7) or a higher value (0.9). When the MEI shock is less persistent the results of the models are quite similar. Actually the key correlations we focused on so far improve in both models, at the expenses of a worse fit of the correlations relative to hours. When the MEI shocks are more persistent, instead, the opposite occurs and the performance of the model deteriorates. This is particularly true for the correlation between consumption growth and investment growth. In the standard model this correlation becomes negative, while in our benchmark model it is slightly positive. This suggests that a value of ρ_I as high as 0.9 would have undesirable implications for medium-scale new keynesian models.

Why are the anomalies in business cycle comovements getting more severe when the MEI shock is more persistent? A high level of persistence for the MEI shock generates a stronger contractionary effect on consumption. To see this, Figure 6 compares the impulse responses of consumption and inflation for different value of the persistence of the MEI shock. The intuition is straightforward: a higher persistence of the MEI shock triggers a stronger and more persistent response of investment. Moreover, forward-looking price setters anticipate it and, when they can, they will reset a higher price generating a stronger and more persistence response of inflation. As a results, the response of consumption is lower the higher the persistence of the shock. When the degree of persistence of the MEI shock is 0.9, the impact response of inflation is about two times the one under our benchmark calibration, and still positive after 15 quarters. Thus consumption drops on impact.[14]

On the one hand, this explains why some business cycle comovements deteriorate with a high level of persistence of the MEI shock. On the other hand, it takes very high value of persistence of the MEI shock to generate a drop in consumption: the response of consumption is still positive when $\rho_I = 0.85$. Moreover, again, our main result still holds. Whatever the degree of persistence of the MEI shock, our benchmark model helps the standard model in breaking the Barro-King curse, by better replicating two key correlations in the business cycle: the one between consumption growth and investment growth and that between consumption growth and output growth.

---

[14]Ascari, Phaneuf, and Sims (2015) shows that the effect of a more persistent MEI shock on the response of inflation is amplified by positive trend inflation, as we have in the model. In the textbook New Keynesian model with sticky prices only, trend inflation makes current inflation more sensitive to expected inflation (Ascari, 2004). A higher persistence of the MEI shock generates higher expected future inflation, that feeds into current inflation the more, the higher is trend inflation.

5 Conclusion

In medium-scale New Keynesian models, monopolistic competition in the goods and labor markets creates a wedge between the marginal rate of substitution between consumption and leisure (MRS) and the marginal product of labor (MPL). Sticky wages and sticky prices make this wedge endogenous. This type of model has proven empirically successful in the recent literature.

In several multi-shock New Keynesian models, investment shocks are typically identified as the one of the main drivers behind business cycle fluctuations. These models are then prone to the Barro-King curse implying some anomalous business cycle comovements, especially when consumption is involved because an improvement in the marginal efficiency of investment typically triggers a short-run contractionary effect on consumption.

In a more general class of business cycle models, the short-run decline in consumption at the onset of a positive investment shock has been addressed through non-standard preferences or a combination of an Edgeworth complementarity between consumption and hours worked with sticky prices. We have offered an alternative approach that combines roundabout production with trend output growth stemming from trend growth in neutral technology and in investment-specific technology. Despite standard preferences, a medium-scale New Keynesian model augmented with these two features is able to remove the Barro-King curse and to be generally consistent with business cycle comovements found in the data. We view these refinements as increasing the empirical plausibility of this class of models and their usefulness in policy analysis.

References

Altig, David, Lawrence J. Christiano, Martin Eichenbaum, and Jesper Lindé. 2011. "Firm-Specific Capital, Nominal Rigidities, and the Business Cycle." *Review of Economic Dynamics* 14(2):225–247.

Ascari, Guido. 2004. "Staggered Prices and Trend Inflation: Some Nuisances." *Review of Economic dynamics* 7 (3):642–667.

Ascari, Guido, Louis Phaneuf, and Eric Sims. 2015. "On the Welfare and Cyclical Implications of Moderate Trend Inflation." NBER Working Paper No. 21392.

Ascari, Guido and Tiziano Ropele. 2009. "Trend Inflation, Taylor Principle and Indeterminacy." *Journal of Money, Credit and Banking* 41 (8):1557–1584.

Barattieri, Alessandro, Susanto Basu, and Peter Gottschalk. 2014. "Some Evidence on the Importance of Sticky Wages." *American Economic Journal: Macroeconomics* 6(1):70–101.

Barro, Robert J. and Robert G. King. 1984. "Time-Separable Preferences and Intertemporal-Substitution Models of Business Cycles." *Quarterly Journal of Economics* 99 (4).

Basu, Susanto. 1995. "Intermediate Goods and Business Cycles: Implications for Productivity and Welfare." *American Economic Review* 85(3):512–531.

Bergin, Paul and Robert Feenstra. 2000. "Staggered price setting, translog preferences, and endogenous persistence." *Journal of Monetary Economics* 45:657–680.

Bils, Mark and Peter J. Klenow. 2004. "Some Evidence on the Importance of Sticky Prices." *Journal of Political Economy* 112(5):947–985.

Calvo, Guillermo A. 1983. "Staggered Prices in a Utility-Maximising Framework." *Journal of Monetary Economics* 12:383–398.

Chari, V. V., Patrick J. Kehoe, and Ellen R. McGrattan. 2009. "New Keynesian Models: Not Yet Useful for Policy Analysis." *American Economic Journal: Macroeconomics* 1(1):242–266.

Christiano, Lawrence J. 2015. "Comment on" Networks and the Macroeconomy: An Empirical Exploration"." In *NBER Macroeconomics Annual 2015, Volume 30*. University of Chicago Press.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy* 113 (1):1–45.

Christiano, Lawrence J., Martin Eichenbaum, and Mathias Trabandt. 2015. "Understanding the Great Recession." *American Economic Journal: Macroeconomics* 7(1):110–167.

———. 2016. "Unemployment and Business Cycles." *Econometrica* 84 (4):1523–1569.

Christiano, Lawrence J., Mathias Trabandt, and Karl Walentin. 2010. "DSGE Models for Monetary Policy Analysis." In *Handbook of Monetary Economics*, edited by Benjamin Friedman and Michael Woodford. Elsevier, 285–367.

Cogley, Timothy and Argia M. Sbordone. 2008. "Trend Inflation, Indexation and Inflation Persistence in the New Keynesian Phillips Curve." *American Economic Review* 98 (5):2101–2126.

Coibion, Olivier and Yuriy Gorodnichenko. 2011. "Monetary Policy, Trend Inflation and the Great Moderation: An Alternative Interpretation." *American Economic Review* 101 (1):341–370.

Cooley, Thomas F. and Edward C. Prescott. 1995. "Economic Growth and Business Cycles." *Frontiers of Business Cycle Research* 1.

Del Negro, Marco, Frank Schorfheide, Frank Smets, and Raf Wouters. 2007. "On the Fit of New-Keynesian Models." *Journal of Business and Economic Statistics* 25 (2):123–143.

Eichenbaum, Martin, Nir Jaimovich, and Sergio Rebelo. 2011. "Reference prices, costs, and nominal rigidities." *The American Economic Review* 101 (1):234–262.

Erceg, Christopher J., Dale W. Henderson, and Andrew T. Levin. 2000. "Optimal Monetary Policy with Staggered Wage and Price Contracts." *Journal of Monetary Economics* 46:281–313.

Eusepi, Stefano and Bruce Preston. 2015. "Consumption heterogeneity, employment dynamics and macroeconomic co-movement." *Journal of Monetary Economics* 71:13 – 32.

Fisher, Jonas. 2006. "The Dynamic Effects of Neutral and Investment-Specific Technology Shocks." *Journal of Political Economy* 114(3):413–451.

Furlanetto, Francesco and Martin Seneca. 2014. "Investment Shocks and Consumption." *European Economic Review* 66:111–126.

Greenwood, Jeremy, Zvi Hercowitz, and Gregory Huffman. 1988. "Investment, Capacity Utilization, and the Real Business Cycle." *American Economic Review* 78(3):402–417.

Greenwood, Jeremy, Zvi Hercowitz, and Per Krusell. 1997. "Long-Run Implications of Investment-Specific Tehnological Change." *American Economic Review* 87(3):342–362.

Huang, Kevin X.D., Zheng Liu, and Louis Phaneuf. 2004. "Why Does the Cyclical Behavior of Real Wages Change Over Time?" *American Economic Review* 94(4):836–856.

Jaimovich, Nir and Sergio Rebelo. 2009. "Can News About the Future Drive the Business Cycle?" *The American Economic Review* 99 (4):1097–1118.

Justiniano, Alejandro and Giorgio Primiceri. 2008. "The Time Varying Volatility of Macroeconomic Fluctuations." *American Economic Review* 98(3):604–641.

Justiniano, Alejandro, Giorgio Primiceri, and Andrea Tambalotti. 2010. "Investment Shocks and Business Cycles." *Journal of Monetary Economics* 57(2):132–145.

———. 2011. "Investment Shocks and the Relative Price of Investment." *Review of Economic Dynamics* 14(1):101–121.

King, Robert. 1991. "Value and Capital in the Equilibrium Business Cycle Program." In *Value and Capital Fifty Years Later*, edited by L. McKenzie and S. Zamagni. London: MacMillan.

Klenow, Peter J. and Benjamin A. Malin. 2011. "Microeconomic Evidence on Price-Setting." In *Handbook of Monetary Economics*, edited by Benjamin M. Friedman and Michael Woodford, chap. 6, Volume 3A. Elsevier, 231–284.

Liu, Zheng and Louis Phaneuf. 2007. "Technology Shocks and Labor Market Dynamics: Some Evidence and Theory." *Journal of Monetary Economics* 54(8):2534–2553.

Nakamura, Emi and Jon Steinsson. 2010. "Monetary Non-Neutrality in a Multi-Sector Menu Cost Model." *Quarterly Journal of Economics* 125 (3):961–1013.

Phaneuf, Louis, Eric Sims, and Jean Gardy Victor. 2015. "Inflation, Output, and Markup Dynamics with Forward-Looking Wage and Price Setters." NBER Working Paper No. 21599.

Rotemberg, Julio J. and Michael Woodford. 1997. "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy." In *NBER Macroeconomics Annual 1997*, edited by Julio J. Rotemberg and B. S. Bernanke. Cambridge, MA, The MIT Press, 297–346.

Smets, Frank and Raf Wouters. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach." *American Economic Review* 97 (3):586–606.

Appendix

A   The Model

This section lays out our medium-scale New Keynesian model. As other similar models, ours embeds standard preferences, nominal rigidities in the form of Calvo (1983) wage and price contracts, habit formation in consumption, investment adjustment costs, variable capital utilization and a Taylor rule.

However, relative to the models of Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007), ours adds the following features. The first feature is the use of intermediate inputs in a so-called "roundabout production" structure (Basu 1995; Huang, Liu, and Phaneuf 2004) or "firms networking". The second feature is real per capita output growth stemming from two distinct sources: trend growth in investment-specific technology (IST) and neutral technology. In the context of our model, trend growth in IST realistically captures the downward secular movement in the relative price of investment observed during the postwar period. The third feature is non-zero trend inflation. We account for positive steady-state inflation because actual inflation has averaged 4 percent (annualized) more or less during the postwar period. A major difference with previous New Keynesian models, however, is that ours omits wage and price indexation either to past or steady-state inflation. The subsections below lay out the decision problems, while the optimality conditions of the relevant model agents are kept for an Appendix.

A.1   Good and Labor Composites

A continuum of firms, indexed by $j \in [0, 1]$, produce differentiated goods with the use of a composite labor input. The composite labor input is aggregated from differentiated labor supplied by a continuum of households, indexed by $i \in [0, 1]$. The differentiated goods are bundled into a gross output good, X_t. Some of this gross output good can be used as a factor of production by firms. Net output is measured as gross output less intermediates, Γ_t. The households can either consume or invest the final net output good. The composite gross output and labor input respectively are:

$$X_t = \left(\int_0^1 X_t(j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}, \tag{10}$$

$$L_t = \left(\int_0^1 L_t(i)^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}}. \tag{11}$$

The parameters $\theta > 1$ and $\sigma > 1$ are the elasticities of substitution between goods and labor. The demand curves for goods and labor are:

$$X_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\theta} X_t, \quad \forall j, \tag{12}$$

$$L_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\sigma} L_t, \quad \forall i. \tag{13}$$

The aggregate price and wage indexes are:

$$P_t^{1-\theta} = \int_0^1 P_t(j)^{1-\theta} dj, \tag{14}$$

$$W_t^{1-\sigma} = \int_0^1 W_t(i)^{1-\sigma} di. \tag{15}$$

A.2   Households

A continuum of households, indexed by $i \in [0,1]$, are monopoly suppliers of labor. They face a downward-sloping demand curve for their particular type of labor given in (13). Each period households face a fixed probability, $(1 - \xi_w)$, that they can adjust their nominal wage. The utility is separable in consumption and labor, and state-contingent securities insure households against idiosyncratic wage risk arising from staggered wage-setting (Erceg, Henderson, and Levin 2000). With this setup, households are identical along all dimensions other than labor supply and wages.

A typical household solves the following problem, omitting dependence on i except for these two dimensions:

$$\max_{C_t, L_t(i), K_{t+1}, B_{t+1}, I_t, Z_t} E_0 \sum_{t=0}^{\infty} \beta^t \varepsilon_t^b \left(\ln(C_t - bC_{t-1}) - \eta \frac{L_t(i)^{1+\chi}}{1+\chi} \right), \tag{16}$$

subject to the following budget constraint,

$$P_t \left(C_t + I_t + \frac{a(Z_t)K_t}{\varepsilon_t^{I,\tau}} \right) + \frac{B_{t+1}}{1+i_t} \leq W_t(i)L_t(i) + R_t^k Z_t K_t + \Pi_t + B_t + T_t, \tag{17}$$

and the physical capital accumulation process,

$$K_{t+1} = \varepsilon_t^{I,\tau} \vartheta_t \left(1 - S\left(\frac{I_t}{I_{t-1}}\right) \right) I_t + (1-\delta)K_t. \tag{18}$$

P_t is the nominal price of goods, C_t is consumption, I_t is investment measured in units of consumption, K_t is the physical capital stock, and Z_t is the level of capital utilization. $W_t(i)$ is the nominal

wage paid to labor of type i, and R_t^k is the common rental price on capital services (the product of utilization and physical capital). Π_t and T_t are the distributed dividends from firms and the lump sum taxes from the government, both of which households take as given. B_t is a stock of nominal bonds that the household enters the period with. $a(Z_t)$ is a resource cost of utilization that satisfies $a(1) = 0$, $a'(1) = 0$, and $a''(1) > 0$. This resource cost is measured in units of physical capital. $S\left(\frac{I_t}{I_{t-1}}\right)$ is an investment adjustment cost that satisfies $S(g_I) = 0$, $S'(g_I) = 0$, and $S''(g_I) > 0$, where $g_I \geq 1$ is the steady state (gross) growth rate of investment. i_t is the nominal interest rate. $0 < \beta < 1$ is the discount factor, $0 < \delta < 1$ is the depreciation rate, and $0 \leq b < 1$ is the parameter for internal habit formation. χ is the inverse Frisch labor supply elasticity.

ε_t^b is an intertemporal preference shock. $\varepsilon_t^{I,\tau}$ enters the capital accumulation equation by multiplying investment and the budget constraint in terms of the resource cost of capital utilization; it measures the level of IST and follows a deterministic trend with no stochastic component. The deterministic trend is necessary to match the actual downward trend in the relative price of investment goods in the data.[15] ϑ_t is a stochastic MEI shock.

A household given the opportunity to adjust its wage in period t chooses a "reset wage" that maximizes the expected value of the discounted flow utility, where discounting in period $t + s$ is $(\beta \xi_w)^s$, ξ_w^s being the probability that a wage chosen in period t will still be in effect in period $t+s$. Given our assumption on preferences and wage-setting, all updating households choose the same reset wage, denoted in real terms by w_t^*. The optimal reset wage is given by:

$$w_t^* = \frac{\sigma}{\sigma - 1} \frac{f_{1,t}}{f_{2,t}}, \tag{19}$$

where the terms $f_{1,t}$ and $f_{2,t}$ can be written recursively as:

$$f_{1,t} = \eta \left(\frac{w_t}{w_t^*}\right)^{\sigma(1+\chi)} L_t^{1+\chi} + \beta \xi_w E_t (\pi_{t+1})^{\sigma(1+\chi)} \left(\frac{w_{t+1}^*}{w_t^*}\right)^{\sigma(1+\chi)} f_{1,t+1}, \tag{20}$$

and

$$f_{2,t} = \lambda_t^r \left(\frac{w_t}{w_t^*}\right)^{\sigma} L_t + \beta \xi_w E_t (\pi_{t+1})^{\sigma-1} \left(\frac{w_{t+1}^*}{w_t^*}\right)^{\sigma} f_{2,t+1}. \tag{21}$$

A.3 Firms

The production function for a typical producer j is:

---

[15] In the model, the relative price of investment goods is $\frac{1}{\varepsilon_t^{I,\tau}}$. Thus, the division by $\varepsilon_t^{I,\tau}$ in the resource cost of utilization is required so that capital is priced in terms of consumption goods.

$$X_t(j) = \max\left\{ A_t\Gamma_t(j)^\phi \left(\widehat{K}_t(j)^\alpha L_t(j)^{1-\alpha}\right)^{1-\phi} - \Upsilon_t F, 0 \right\}, \tag{22}$$

where F is a fixed cost, and production is required to be non-negative. Υ_t is a growth factor. Given Υ_t, F is chosen to ensure zero profits along a balanced growth path, so the entry and exit of firms can be ignored. $\Gamma_t(j)$ is the amount of intermediate inputs, and $\phi \in (0,1)$ is the intermediate input share. Intermediate inputs come from aggregate gross output, X_t. $\widehat{K}_t(j)$ is capital services or the product of utilization and physical capital, while $L_t(j)$ is labor input. This production function differs from the standard specification in the New Keynesian DSGE literature by adding intermediate inputs, $\Gamma_t(j)$, allowing for roundaboutness in the production structure or firms networking.

The firm gets to choose its price, $P_t(j)$, as well as quantities of intermediates, capital services, and labor input. Each period firms face a probability $(1 - \xi_p)$ that they can adjust their price. Regardless of whether a firm is given the opportunity to adjust its price, it will choose inputs to minimize total cost, subject to the constraint of producing enough to meet demand. The cost minimization problem of a typical firm is:

$$\min_{\Gamma_t, \widehat{K}_t, L_t} \quad P_t\Gamma_t + R_t^k \widehat{K}_t + W_t L_t \tag{23}$$

s.t.

$$A_t\Gamma_t^\phi \left(\widehat{K}_t^\alpha L_t^{1-\alpha}\right)^{1-\phi} - \Upsilon_t F \geq \left(\frac{P_t(j)}{P_t}\right)^{-\theta} X_t$$

Applying some algebraic manipulations to the first order conditions for cost-minimization yields the following expression for real marginal cost, v_t, which is common across firms:

$$v_t = \overline{\phi} A_t^{-1} \left(r_t^k\right)^{\alpha(1-\phi)} w_t^{(1-\alpha)(1-\phi)}, \tag{24}$$

where $\overline{\phi}$ is a constant. This expression for real marginal cost can be compared to the expression we get in the standard model that abstracts from intermediate inputs ($\phi = 0$):

$$v_t = \overline{\alpha} A_t^{-1}(r_t^k)^\alpha (w_t)^{1-\alpha}, \tag{25}$$

where $\overline{\alpha}$ is a constant.

A firm given the opportunity to adjust its price maximizes the expected discounted value of profits, where discounting in period $t + s$ is by the stochastic discount factor as well as ξ_p^s, ξ_p^s being

the probability that a price chosen in period t will still be in effect in period $t + s$. All updating firms choose the same reset price. Let $p_t^* \equiv \frac{P_t^*}{P_t}$ be the optimal reset price relative to the aggregate price index. The optimal pricing condition can be written:

$$p_t^* = \frac{\theta}{\theta - 1} \frac{x_{1,t}}{x_{2,t}}, \tag{26}$$

where the auxiliary variables $x_{1,t}$ and $x_{2,t}$ can be written recursively:

$$x_{1,t} = \lambda_t^r v_t X_t + \beta \xi_p E_t (\pi_{t+1})^\theta x_{1,t+1}, \tag{27}$$

$$x_{2,t} = \lambda_t^r X_t + \beta \xi_p E_t (\pi_{t+1})^{\theta-1} x_{1,t+1}, \tag{28}$$

where λ_t^r is the marginal utility of an additional unit of real income received by the household.

A.4 Monetary Policy

Monetary policy is described by the following Taylor rule:

$$\frac{1 + i_t}{1 + i} = \left(\frac{1 + i_{t-1}}{1 + i} \right)^{\rho_i} \left[\left(\frac{\pi_t}{\pi} \right)^{\alpha_\pi} \left(\frac{Y_t}{Y_{t-1}} g_Y^{-1} \right)^{\alpha_y} \right]^{1-\rho_i} \varepsilon_t^r. \tag{29}$$

According to this specification, the FED adjusts the nominal interest rate in response to deviations of inflation from an exogenous steady-state inflation target, π, and to deviations of output growth from its steady-state level, g_Y. ε_t^r is a white-noise exogenous shock to the policy rule. ρ_i is a smoothing parameter while α_π and α_y are two control parameters.

A.5 Shock Processes

The intertemporal preference shock ε_t^b follows a stationary AR(1) process:

$$\varepsilon_t^b = (\varepsilon_{t-1}^b)^{\rho_b} \exp(s_b u_t^b), \tag{30}$$

with innovation u_t^b drawn from a mean zero normal distribution with standard deviation s_b.

Neutral productivity obeys a process with both a trending and stationary component. A_t^τ is the deterministic trend component, where g_A is the gross growth rate:

$$A_t = A_t^\tau \widetilde{A}_t, \tag{31}$$

$$A_t^\tau = g_A A_{t-1}^\tau. \tag{32}$$

The initial level in period 0 is normalized to 1: $A_0^\tau = 1$. The stationary component of neutral productivity follows an AR(1) process in the log, with the non-stochastic mean level normalized to unity, and innovation, u_t^A, drawn from a mean zero normal distribution with known standard deviation equal to s_A:

$$\widetilde{A}_t = \left(\widetilde{A}_{t-1}\right)^{\rho_A} \exp\left(s_A u_t^A\right), \quad 0 \le \rho_A < 1, \tag{33}$$

The IST term obeys the following deterministic trend, where g_{ε^I} is the gross growth rate and the initial level in period 0 is normalized to unity:

$$\varepsilon_t^{I,\tau} = g_{\varepsilon^I} \varepsilon_{t-1}^{I,\tau} \tag{34}$$

The MEI shock follows a stationary AR(1) process, with innovation u_t^I drawn from a mean zero normal distribution with standard deviation s_I:

$$\vartheta_t = (\vartheta_{t-1})^{\rho_I} \exp(s_I u_t^I), \quad 0 \le \rho_I < 1 \tag{35}$$

The only remaining shock in the model is the monetary policy shock, ε_t^r. We assume that is drawn from a mean zero normal distribution with known standard deviation s_r.

A.6   Functional Forms

The resource cost of utilization and the investment adjustment cost function have the functional forms:

$$a(Z_t) = \gamma_1(Z_t - 1) + \frac{\gamma_2}{2}(Z_t - 1)^2, \tag{36}$$

$$S\left(\frac{I_t}{I_{t-1}}\right) = \frac{\kappa}{2}\left(\frac{I_t}{I_{t-1}} - g_I\right)^2, \tag{37}$$

where $\gamma_2 > 0$ is a free parameter; as $\gamma_2 \to \infty$ utilization is fixed at unity. γ_1 must be restricted so that the optimality conditions are consistent with the normalization of steady state utilization of 1. $\kappa \ge 0$ is a free parameter. The functional form for the investment adjustment cost is standard in the literature (e.g., Christiano, Eichenbaum, and Evans 2005).

A.7   Growth

Most variables in the model inherit trend growth from the deterministic trends in neutral and investment-specific productivity. Suppose that this trend factor is Υ_t. Output, consumption, investment, intermediate inputs, and the real wage all grow at the rate of this trend factor on a

balanced growth path: $g_Y = g_I = g_\Gamma = g_w = g_\Upsilon$. The capital stock grows faster due to growth in investment-specific productivity, with $\widetilde{K}_t \equiv \frac{K_t}{\Upsilon_t \varepsilon_t^{I,\tau}}$ being stationary. Given our specification of preferences, labor hours are stationary. The full set of equilibrium conditions re-written in stationary terms can be found in the Appendix.

The trend factor inducing stationarity among transformed variables is:

$$\Upsilon_t = (A_t^\tau)^{\frac{1}{(1-\phi)(1-\alpha)}} \left(\varepsilon_t^{I,\tau}\right)^{\frac{\alpha}{1-\alpha}} . \tag{38}$$

When there are no intermediate inputs, this expression reverts to the conventional trend growth factor in a model with growth in neutral and investment-specific productivity. The model then reduces to the standard New Keynesian model. Interestingly, from (38), it is evident that a higher value of the share of intermediate inputs ϕ amplifies the effects of trend growth in neutral productivity on output and its components.

A.8   Full Set of Equilibrium Conditions

This Appendix lists the full set of stationarized equations which characterize the equilibrium of our model. Variables with a $\sim$ denote transformed variables which are stationary

$$\widetilde{\lambda}_t^r = \frac{\varepsilon_t^b}{\widetilde{C}_t - b g_\Upsilon^{-1} \widetilde{C}_{t-1}} - E_t \frac{\beta b \varepsilon_{t+1}^b}{g_\Upsilon \widetilde{C}_{t+1} - b \widetilde{C}_t} \tag{A 1}$$

$$\widetilde{r}_t^k = \gamma_1 + \gamma_2 (Z_t - 1) \tag{A 2}$$

$$\widetilde{\lambda}_t^r = \widetilde{\mu}_t \vartheta_t \left(1 - \frac{k}{2}\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_\Upsilon - g_\Upsilon\right)^2 - \kappa \left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_\Upsilon - g_\Upsilon\right)\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_\Upsilon\right) + \beta E_t g_\Upsilon^{-1}\widetilde{\mu}_{t+1}\vartheta_{t+1}\kappa\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}g_\Upsilon - g_\Upsilon\right)\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}g_\Upsilon\right)^2 \tag{A 3}$$

$$g_I g_\Upsilon \widetilde{\mu}_t = \beta E_t \widetilde{\lambda}_{t+1}^r \left(\widetilde{r}_{t+1}^k Z_{t+1} - \left(\gamma_1(Z_{t+1} - 1) + \frac{\gamma_2}{2}(Z_{t+1} - 1)^2\right)\right) + \beta(1-\delta)E_t \widetilde{\mu}_{t+1} \tag{A 4}$$

$$\widetilde{\lambda}_t^r = \beta g_\Upsilon^{-1} E_t (1 + i_t) \pi_{t+1}^{-1} \widetilde{\lambda}_{t+1}^r \tag{A 5}$$

$$\widetilde{w}_t^* = \frac{\sigma}{\sigma - 1}\frac{f_{1,t}}{\widetilde{f}_{2,t}} \tag{A 6}$$

$$\widetilde{f}_{1,t} = \eta\left(\frac{\widetilde{w}_t}{\widetilde{w}_t^*}\right)^{\sigma(1+\chi)} L_t^{1+\chi} + \beta \xi_w E_t (\pi_{t+1})^{\sigma(1+\chi)}\left(\frac{\widetilde{w}_{t+1}^*}{\widetilde{w}_t^*}\right)^{\sigma(1+\chi)} g_\Upsilon^{\sigma(1+\chi)}\widetilde{f}_{1,t+1} \tag{A 7}$$

$$\widetilde{f}_{2,t} = \widetilde{\lambda}_t^r \left(\frac{\widetilde{w}_t}{\widetilde{w}_t^*}\right)^{\sigma} L_t + \beta \xi_w E_t (\pi_{t+1})^{\sigma-1}\left(\frac{\widetilde{w}_{t+1}^*}{\widetilde{w}_t^*}\right)^{\sigma} g_\Upsilon^{\sigma-1}\widetilde{f}_{2,t+1} \tag{A 8}$$

$$\widetilde{\widetilde{K}}_t = g_I g_\Upsilon \alpha (1-\phi)\frac{mc_t}{\widetilde{r}_t^k}\left(s_t \widetilde{X}_t + F\right) \tag{A 9}$$

$$L_t = (1 - \alpha)(1 - \phi)\frac{mc_t}{\widetilde{w}_t}\left(s_t\widetilde{X}_t + F\right) \tag{A 10}$$

$$\widetilde{\Gamma}_t = \phi mc_t\left(s_t\widetilde{X}_t + F\right) \tag{A 11}$$

$$p_t^* = \frac{\theta}{\theta - 1}\frac{x_t^1}{x_t^2} \tag{A 12}$$

$$x_t^1 = \widetilde{\lambda}_t^r mc_t\widetilde{X}_t + \xi_p\beta\left(\frac{1}{\pi_{t+1}}\right)^{-\theta}x_{t+1}^1 \tag{A 13}$$

$$x_t^2 = \widetilde{\lambda}_t^r\widetilde{X}_t + \xi_p\beta\left(\frac{1}{\pi_{t+1}}\right)^{1-\theta}x_{t+1}^2 \tag{A 14}$$

$$1 = \xi_p\left(\frac{1}{\pi_t}\right)^{1-\theta} + (1 - \xi_p)p_t^{*1-\theta} \tag{A 15}$$

$$\widetilde{w}_t^{1-\sigma} = \xi_w g_\Upsilon^{\sigma-1}\left(\frac{\widetilde{w}_{t-1}}{\pi_t}\right)^{1-\sigma} + (1 - \xi_w)\widetilde{w}_t^{*1-\sigma} \tag{A 16}$$

$$\widetilde{Y}_t = \widetilde{X}_t - \widetilde{\Gamma}_t \tag{A 17}$$

$$s_t\widetilde{X}_t = \widetilde{A}_t\widetilde{\Gamma}_t^\phi\widetilde{\widetilde{K}}_t^{\alpha(1-\phi)}L_t^{(1-\alpha)(1-\phi)}g_\Upsilon^{\alpha(\phi-1)}g_I^{\alpha(\phi-1)} - F \tag{A 18}$$

$$\widetilde{Y}_t = \widetilde{C}_t + \widetilde{I}_t + g_\Upsilon^{-1}g_I^{-1}\left(\gamma_1(Z_t - 1) + \frac{\gamma_2}{2}(Z_t - 1)^2\right)\widetilde{K}_t \tag{A 19}$$

$$\widetilde{K}_{t+1} = \vartheta_t\left(1 - \frac{\kappa}{2}\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_\Upsilon - g_\Upsilon\right)^2\right)\widetilde{I}_t + (1 - \delta)g_\Upsilon^{-1}g_I^{-1}\widetilde{K}_t \tag{A 20}$$

$$\frac{1 + i_t}{1 + i} = \left(\left(\frac{\pi_t}{\pi}\right)^{\alpha_\pi}\left(\frac{\widetilde{Y}_t}{\widetilde{Y}_{t-1}}\right)^{\alpha_y}\right)^{1-\rho_i}\left(\frac{1 + i_{t-1}}{1 + i}\right)^{\rho_i}\varepsilon_t^r \tag{A 21}$$

$$\widetilde{\widetilde{K}}_t = Z_t\widetilde{K}_t \tag{A 22}$$

$$s_t = (1 - \xi_p)p_t^{*-\theta} + \xi_p\left(\frac{1}{\pi_t}\right)^{-\theta}s_{t-1} \tag{A 23}$$

$$v_t^w = (1 - \xi_w)\left(\frac{\widetilde{w}_t^*}{\widetilde{w}_t}\right)^{-\sigma(1+\chi)} + \xi_w\left(\frac{\widetilde{w}_{t-1}}{\widetilde{w}_t}g_\Upsilon^{-1}\frac{1}{\pi_t}\right)^{-\sigma(1+\chi)}v_{t-1}^w \tag{A 24}$$

B   Calibration

Our baseline calibration of the model's parameters is divided in two groups: non-shock and shock parameters.

B.1 Non-Shock Parameters

The values of non-shock parameters are summarized in Table 1. $\beta = 0.99$ is the discount factor, $b = 0.7$ is the habit formation parameter, $\chi = 1$ is the inverse Frisch elasticity, and $\eta = 6$ is the weight on disutility of labor set so that steady-state labor hours are around 1/3. The parameters in the production function are the share of capital services $\alpha = 1/3$ and the share of intermediate inputs $\phi = 0.61$. The $\phi-$values used in the literature broadly range from 0.5 to 0.8. As explained in the main text, we set the value for ϕ as follows. Following Nakamura and Steinsson (2010), we take the weighted average revenue share of intermediate inputs in the U.S. private sector using Consumer Price Index (CPI) expenditure weights to be roughly 51 percent in 2002. Now, the cost share of intermediate inputs is equal to the revenue share times the price markup. Since the elasticities for goods and labor, θ and σ, are both set equal to 6 (e.g., Rotemberg and Woodford, 1997; Liu and Phaneuf, 2007), our calibration of θ implies a markup of 1.2. Therefore, our estimate of the weighted average cost share of intermediate inputs is roughly 0.61.[16] The depreciation rate on physical capital is $\delta = 0.025$. $\kappa = 3$ is the investment adjustment cost parameter. γ_1 is set so that steady state utilization is 1. The parameter γ_2 is set to 0.05. The parameter values for δ, κ, γ_1 and γ_2 are consistent with the evidence reported in Justiniano, Primiceri, and Tambalotti (2010, 2011).

The Calvo probabilities of wage and price non-adjustments, ξ_w and ξ_p, are both set equal to 2/3, implying an average duration of wage and price contracts of 3 quarters or 9 months. The average frequency of price adjustments in our model is therefore lower than suggested by the evidence in Bils and Klenow (2004) for the years 1995-1997 and Christiano, Eichenbaum, and Evans (2005), but can be viewed as conservative in light of the evidence in Eichenbaum, Jaimovich, and Rebelo (2011) and Klenow and Malin (2011) suggesting that prices remain fixed for relatively long periods of time.[17] The average frequency of wage adjustments is somewhat lower than suggested by the estimates in Christiano, Eichenbaum, and Evans (2005), but higher than implied by the estimates in Justiniano, Primiceri, and Tambalotti (2010, 2011) and Barattieri, Basu, and Gottschalk (2014). Overall, we view these values of ξ_w and ξ_p as midway between microeconomic and macroeconomic evidence on the frequency of wages and price changes.

The last three parameters are the smoothing parameter which is set at 0.8, the coefficient on the deviations of inflation from the inflation target set at 1.5, and the coefficient on the deviations of output growth from steady state set at 0.2. These values are fairly standard in the literature.

---

[16]The steady-state price markup is for a trend inflation of zero. We find that this markup is almost insensitive to trend inflation between 0 and 4 percent leaving ϕ unaffected as trend inflation rises.

[17]We do admit, however, that these authors sometimes question the relevance of the Calvo price-setting framework to explain their evidence on nominal price rigidity. We do not address this issue here.

B.2 Trend Inflation and Trend Growth

Next, we turn our attention to the calibration of the parameters governing trend inflation and trend output growth. Table 2 summarizes these parameter values.

The average growth rate of the price index over the period 1960:I-2007:III is 0.008675. This implies $\pi^* = 1.0088$ or 3.52 percent annualized.

As explained in the main text, mapping the model to the data, the trend growth rate of the IST term, $g_{\varepsilon I}$, equals the negative of the growth rate of the relative price of investment goods. To measure this in the data, we define investment as expenditures on new durables plus private fixed investment, and consumption as consumer expenditures of nondurables and services. These series are from the BEA and cover the period 1960:I-2007:III.[18] The relative price of investment is the ratio of the implied price index for investment goods to the price index for consumption goods. The average growth rate of the relative price from the period 1960:I-2007:III is -0.00472. This implies a calibration of $g_{\varepsilon I} = 1.00472$. Real per capita GDP is computed by subtracting from the log-level the log civilian non-institutionalized population. The average growth rate of the resulting output per capita series over the period is 0.005712. The standard deviation of output growth over the period is 0.0078. The calculations above imply that $g_Y = 1.005712$ or 2.28 percent a year. Given the calibrated growth of IST from the relative price of investment data ($g_{\varepsilon I} = 1.00472$), we then pick $g_A^{1-\phi}$ to generate the appropriate average growth rate of output. This implies $g_A^{1-\phi} = 1.0022$ or a measured growth rate of TFP of about 1 percent per year.

---

[18] A detailed explanation of how these data are constructed can be found in Ascari, Phaneuf, and Sims (2015).

Table 1: Non-Shock Parameters

β	δ	α	η	χ	b	κ	γ_2
0.99	0.025	1/3	6	1	0.7	3	0.005
θ	σ	ξ_p	ξ_w	ϕ	ρ_i	α_π	α_y
6	6	0.66	0.66	0.61	0.8	1.5	0.2

Note: this table gives the baseline values of the parameters unrelated to the stochastic processes used in our quantitative simulations.

Table 2: Standard Values for Shock Parameters

g_A	g_{ε^I}	ρ_b	ρ_I	ρ_A
$1.0022^{1-\phi}$	1.0047	0.6	0.8	0.95

Note: this table gives the baseline values of the parameters of the stochastic processes used in our quantitative simulations. The trend growth rate of the IST process is chosen to match the average growth rate of the relative price of investment goods in the data. The trend growth growth of the neutral productivity process is chosen to match the average growth rate of output observed in the sample conditional on the growth rate of the IST process.

Table 3: The Size of Shocks in Alternative Models - Benchmark Case

	Alternative Models			
Shocks	No FN/No G	FN/G	No FN/G	FN/No G
s_I	0.0287	0.0194	0.0244	0.0234
s_A	0.0069	0.0027	0.0064	0.0029
s_b	0.0086	0.0083	0.0084	0.0084
s_r	0.0019	0.0015	0.0017	0.0016

Note: this table gives the values of the shock standard deviations used in alternative models. Given the assumed values of autoregressive parameters governing the stochastic processes, the shock standard deviations are chosen to match the volatility of output growth in the data with an annualized trend inflation of 3.52 percent. Benchmark case: the MEI shock accounts for 60 percent of the variance of output growth, the neutral technology shock for 25 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Table 4: Moments in the Benchmark and standard New Keynesian Model

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$	$\rho(\mathbf{\Delta Y, \Delta C})$
Data	(0.0047)	(0.0202)	(0.0079)	**(0.7542)**
Standard New Keynesian	0.0044	0.0264	0.0105	**0.3889**
Benchmark	0.0048	0.0194	0.0078	**0.7030**
No FN / Growth	0.0045	0.0217	0.0098	0.5262
FN / No Growth	0.0045	0.0240	0.0084	0.5840
	$\rho(\Delta Y, \Delta I)$	$\rho(\mathbf{\Delta C, \Delta I})$	$\rho(\Delta Y, L)$	$\rho(\Delta C, L)$
Data	(0.9192)	**(0.4362)**	(0.1105)	(0.0746)
Standard New Keynesian	0.8892	**-0.0481**	0.0383	0.0147
Benchmark	0.9021	**0.3562**	-0.0001	0.0298
No FN/ Growth	0.8933	0.1256	0.0317	0.0737
FN / No Growth	0.8999	0.1941	0.0166	-0.0048

Note: this table shows selected moments generated from the standard New Keynesian model (i.e., No FN/ no Growth), from our benchmark model with FN and growth, from a model with no FN and growth (i.e., No FN / Growth) and from a model with FN and no growth (i.e., FN / No Growth) . "σ " denotes standard deviation, "Δ " refers to the first difference operator, and ρ is a coefficient of correlation. The variables Y, I, C, and L are the natural logs of these series. Moments in the data are computed for the sample 1960q1-2007q3 and are shown in parentheses.

Table 5: The Size of Shocks in Alternative Models - Split 1 and 2

		Alternative Models			
(a) Shocks Split 1		No FN/No G	FN/G	No FN/G	FN/No G
	s_I	0.0315	0.0212	0.0267	0.0256
	s_A	0.0058	0.0022	0.0054	0.0024
	s_b	0.0086	0.0082	0.0084	0.0083
	s_r	0.0019	0.0015	0.0017	0.0016
(b) Shocks Split 2					
	s_I	0.0257	0.0173	0.0218	0.0210
	s_A	0.0078	0.0030	0.0073	0.0033
	s_b	0.0086	0.0082	0.0084	0.0084
	s_r	0.0019	0.0015	0.0017	0.0016

Note: this table gives the values of the shock standard deviations used in alternative models. The shock standard deviations are chosen to match the volatility of output growth in the data with an annualized trend inflation of 3.52 percent. Split 1: the MEI shock accounts for 60 percent of the variance of output growth, the neutral technology shock for 25 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. Split 2: the MEI shock accounts for 40 percent of the variance of output growth, the neutral technology shock for 45 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Table 6: Moments for alternative Models for different Splits of relative importance of shocks

Panel A: Split 1

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$	$\rho(\Delta Y, \Delta C)$
Data	(0.0047)	(0.0202)	(0.0079)	(0.7542)
Standard New Keynesian	0.0042	0.0281	0.0100	0.2610
Benchmark	0.0045	0.0205	0.0073	0.6458
No FN / Growth	0.0042	0.0231	0.0093	0.4266
FN / No Growth	0.0042	0.0254	0.0079	0.4957
	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, L)$	$\rho(\Delta C, L)$
Data	(0.9192)	(0.4362)	(0.1105)	(0.0746)
Standard New Keynesian	0.9003	-0.1628	0.1146	0.0960
Benchmark	0.9117	0.3001	0.0900	0.1551
No FN/ Growth	0.9035	0.0303	0.1051	0.1685
FN / No Growth	0.9098	0.1090	0.1055	0.1071

Panel B: Split 2

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$	$\rho(\Delta Y, \Delta C)$
Data	(0.0047)	(0.0202)	(0.0079)	(0.7542)
Standard New Keynesian	0.0046	0.0246	0.0111	0.5075
Benchmark	0.0051	0.0181	0.0083	0.7561
No FN / Growth	0.0047	0.0203	0.0103	0.6173
FN / No Growth	0.0048	0.0224	0.0090	0.6641
	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, L)$	$\rho(\Delta C, L)$
Data	(0.9192)	(0.4362)	(0.1105)	(0.0746)
Standard New Keynesian	0.8806	0.0720	-0.0458	-0.0681
Benchmark	0.8949	0.4176	-0.0987	-0.0898
No FN/ Growth	0.8856	0.2248	-0.0479	-0.0183
FN / No Growth	0.8925	0.2822	-0.0802	-0.1123

Note: this table shows selected moments generated from the standard New Keynesian model (with no FN and no Growth), from our benchmark model with FN and growth, from a model with no FN and growth (i.e., No FN / Growth) and from a model with FN and no growth (i.e., FN / No Growth) . "σ " denotes standard deviation, "Δ " refers to the first difference operator, and ρ is a coefficient of correlation. The variables Y, I, C, and L are the natural logs of these series. Moments in the data are computed for the sample 1960q1-2007q3 and are shown in parentheses. Split 1: the MEI shock accounts for 60 percent of the variance of output growth, the neutral technology shock for 25 percent, the monetary policy shock for 7 p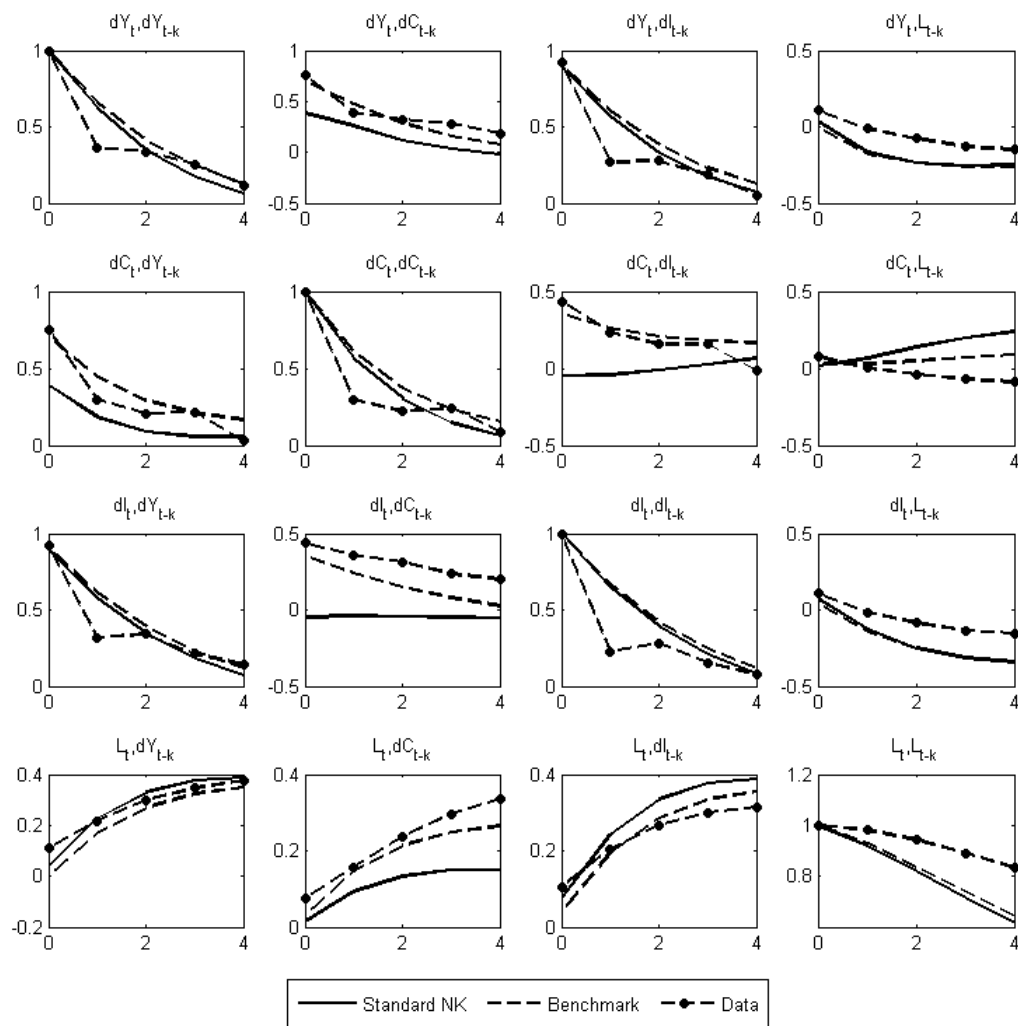ercent, and the preference shock for 8 percent. Split 2: the MEI shock accounts for 40 percent of the variance of output growth, the neutral technology shock for 45 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Table 7: Moments for alternative Models for different degree of persistence of the MEI shock

Panel A: $\rho_I = 0.7$

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$	$\rho(\Delta Y, \Delta C)$
Data	(0.0047)	(0.0202)	(0.0079)	(0.7542)
Standard New Keynesian	0.0042	0.0244	0.0105	0.5148
Benchmark	0.0048	0.0189	0.0078	0.7302
No FN / Growth	0.0043	0.0204	0.0098	0.6142
FN / No Growth	0.0044	0.0229	0.0084	0.6454
	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, L)$	$\rho(\Delta C, L)$
Data	(0.9192)	(0.4362)	(0.1105)	(0.0746)
Standard New Keynesian	0.9011	0.1215	0.0017	-0.0516
Benchmark	0.9067	0.4019	-0.0360	-0.0402
No FN/ Growth	0.9037	0.2549	0.0019	0.0094
FN / No Growth	0.9073	0.2869	-0.0270	-0.0781

Panel B: $\rho_I = 0.9$

|	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$	$\rho(\Delta Y, \Delta C)$
Data	(0.0047)	(0.0202)	(0.0079)	(0.7542)
Standard New Keynesian	0.0058	0.0328	0.0105	0.0869
Benchmark	0.0052	0.0222	0.0078	0.5332
No FN / Growth	0.0057	0.0272	0.0098	0.2136
FN / No Growth	0.0051	0.0279	0.0085	0.3642
	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, L)$	$\rho(\Delta C, L)$
Data	(0.9192)	(0.4362)	(0.1105)	(0.0746)
Standard New Keynesian	0.8517	-0.4256	0.1329	0.1382
Benchmark	0.8746	0.0871	0.0802	0.1490
No FN/ Growth	0.8488	-0.3001	0.1071	0.1673
FN / No Growth	0.8714	-0.1183	0.1208	0.1327

Note: this table shows selected moments generated from the standard New Keynesian model (with no FN and no Growth), from our benchmark model with FN and growth, from a model with no FN and growth (i.e., No FN / Growth) and from a model with FN and no growth (i.e., FN / No Growth) . "σ " denotes standard deviation, "Δ " refers to the first difference operator, and ρ is a coefficient of correlation. The variables Y, I, C, and L are the natural logs of these series. Moments in the data are computed for the sample 1960q1-2007q3 and are shown in parentheses. Split 1: the MEI shock accounts for 60 percent of the variance of output growth, the neutral technology shock for 25 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. Split 2: the MEI shock accounts for 40 percent of the variance of output growth, the neutral technology shock for 45 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Figure 1: Cross-correlogram of the key macroeconomic variables in the benchmark model

Note: this figure plots the cross-correlations of output, consumption, investment, and hours in the data, in the benchmark (FN/G) model and in the standard New Keynesian (No FN/No G) one, for our benchmark calibration: the MEI shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.
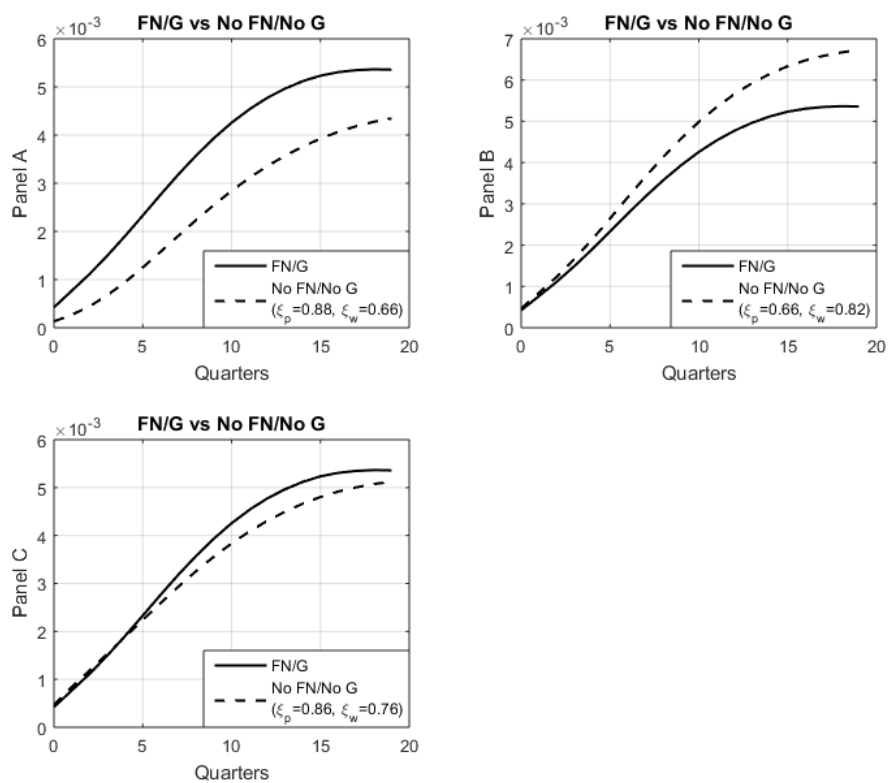
Figure 2: Impulse Responses to MEI Schock
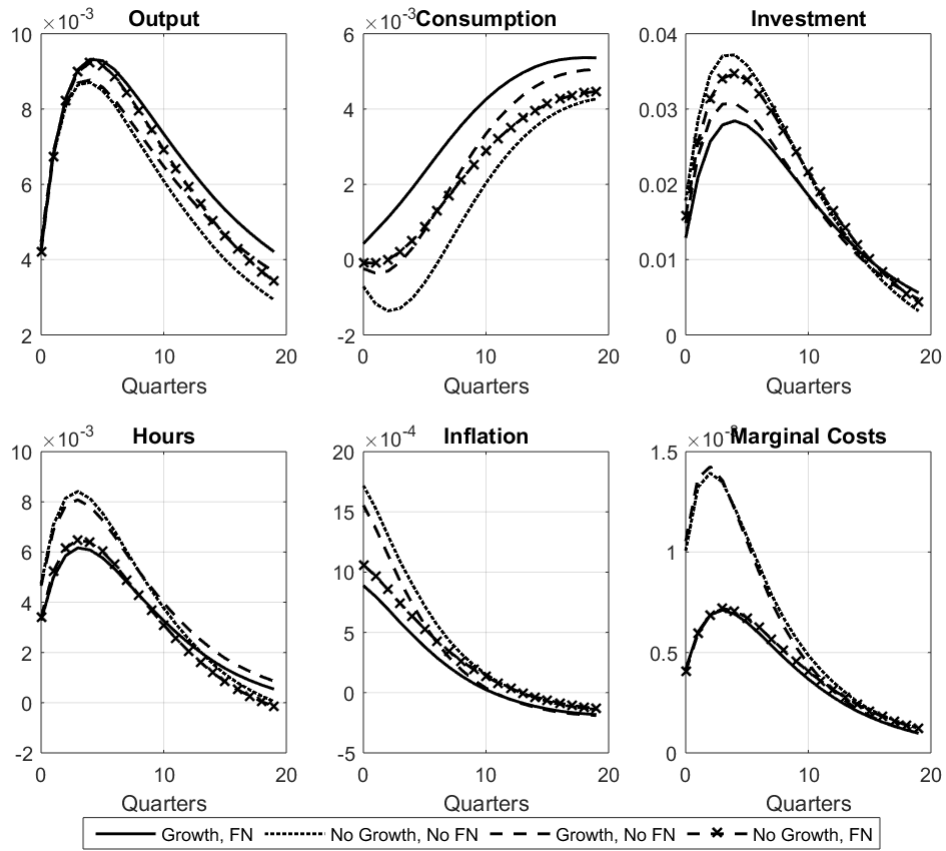
Note: this figure plots the impulse response of output, consumption, investment, hours, inflation and marginal costs for our benchmark calibration: the MEI shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. It does so for 4 versions of the model: our benchmark model with FN and growth, the standard New Keynesian model (with no FN and no Growth), the model with no FN and growth (i.e., No FN / Growth) and the model with FN and no growth (i.e., FN / No Growth).

Figure 3: Hicksian decomposition according to King (1991)
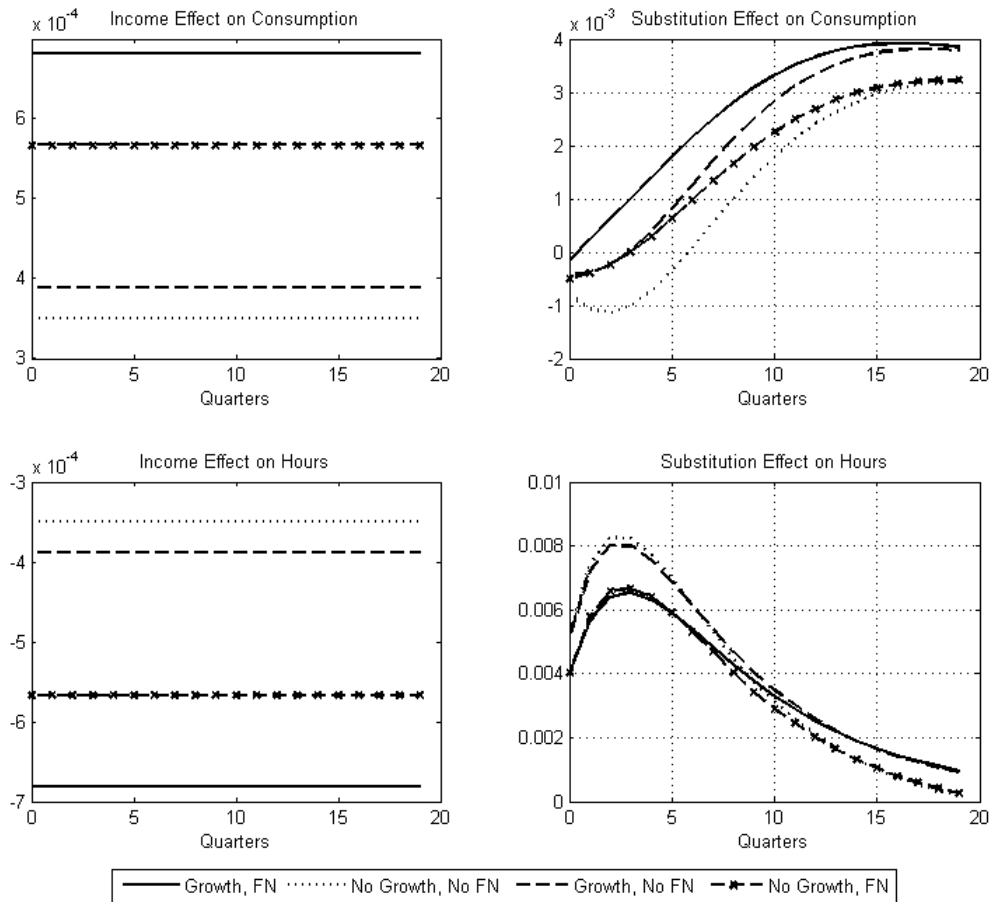
Note: this figure plots the income and substitution effects according to the Hicksian decomposition in King (1991) for our benchmark calibration. It does so for 4 versions of the model: our benchmark model with FN and growth, the standard New Keynesian model (with no FN and no Growth), the model with no FN and growth (i.e., No FN / Growth) and the model with FN and no growth (i.e., FN / No Growth).

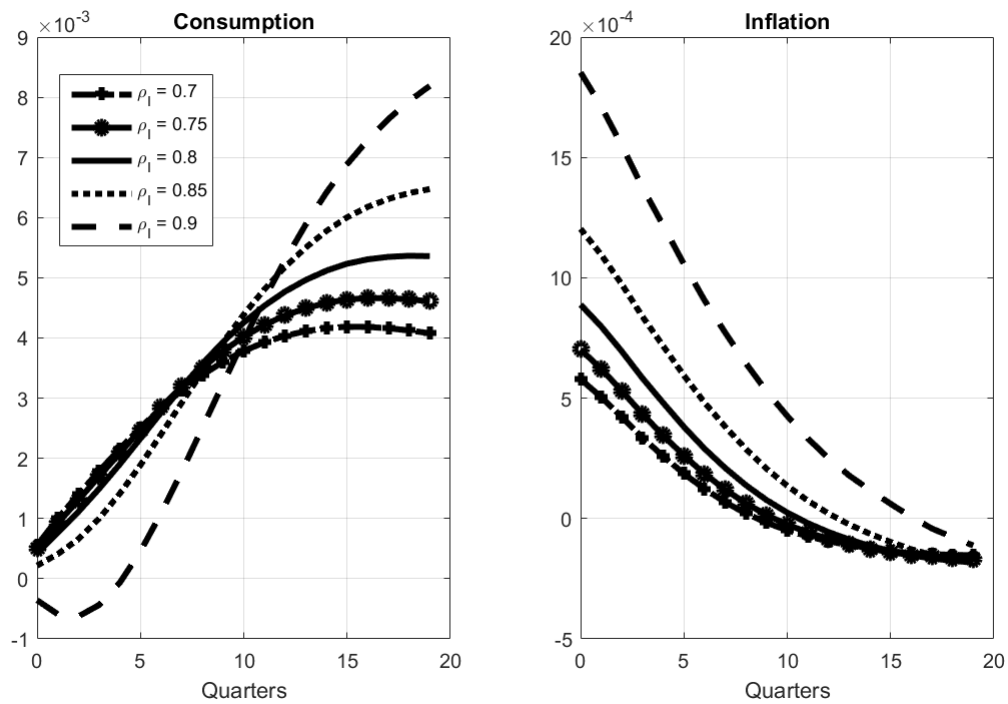Figure 4: Impulse Responses of Consumption to a MEI Shock

Note: this figure plots the impulse response of consumption to a positive MEI shock in the benchmark (FN/G) and standard New Keynesian (No FN/No G) models. For the standard model, we consider values of the Calvo probabilities of wage and price non reoptimization for which the impact response of consumption to a MEI shock matches that from the FN/G model.

Figure 5: Cross-correlogram of the key macroeconomic variables in the benchmark model for alternative splits
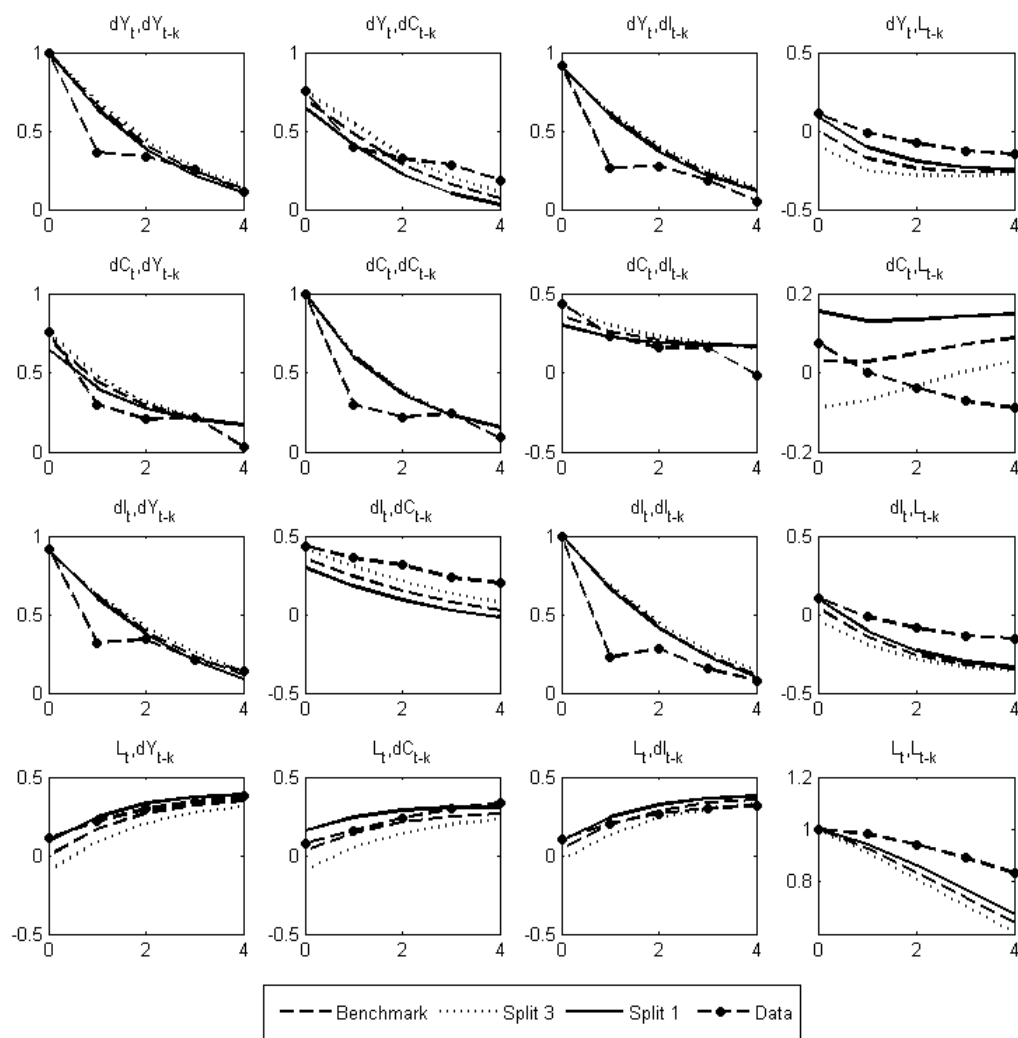
Note: this figure plots the cross-correlations of output, consumption, investment, and hours for our benchmark calibration for alternative splits. Benchmark: the MEI shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. Split 1: the MEI shock accounts for 60 percent of the variance of output growth, the neutral technology shock for 25 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. Split 2: the MEI shock accounts for 40 percent of the variance of output growth, the neutral technology shock for 45 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Figure 6: Impulse Responses of Consumption and Inflation to a MEI Shock for different persistence

Note: this figure plots the impulse response of consumption and inflation to a positive MEI shock in the benchmark model for different levels of persistence of the MEI shock, given our benchmark calibration: the MEI shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.