Can New Keynesian Models Survive the Barro-King Curse?

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Abstract

Barro and King (1984) conjecture that shocks other than those to total factor productivity will have difficulty generating key business cycle comovements between output, consumption, investment and hours worked. Recent years have seen the emergence of a class of DSGE models in which aggregate fluctuations are driven by several shocks, making them particularly vulnerable to the "Barro-King Curse". These models emphasize monopolistically competitive goods and labor markets, nominal rigidities and real frictions. We show that the standard medium-scale New Keynesian model is vulnerable to the curse predicting anomalous contemporaneous correlations between key variables and wrong profiles of cross-correlations. With the realistic additions of roundabout production and real per capita output growth, the New Keynesian model can survive the curse despite standard preferences, a cost of capital utilization measured as foregone consumption and positive trend inflation.

JEL classification: E31, E32.

Keywords: Monopolistic competition; Nominal wage and price rigidities; Firms networking; Trend output growth; Trend inflation; Business cycle comovements.

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1 Introduction

Shortly after the publication of Kydland and Prescott (1982) seminal paper arguing that shocks to total factor productivity (TFP) are the key source of business cycle fluctuations, Barro and King (1984) have conjectured that shocks other than those to TFP will have difficulty matching the actual comovements between output, consumption, investment and hours, a conjecture we refer to as the "Barro-King curse".

For example, consider what happens from a neoclassical perspective after a positive investment shock. This shock will increase the rate of return on investment, creating an incentive for households to save (or invest) more and postpone consumption for the future. This will result into an investment boom and a short-run decline in consumption, so that the correlation between consumption growth and investment growth will be negative unlike what the data tell us insofar as the investment shock is a key disturbance driving business cycle fluctuations.

While at the origin the curse has been formulated in a neoclassical environment, it has prevailed in other contexts as well. An example is the recent class of medium-scale New Keynesian (MSNK) models in which investment shocks are found to be empirically important (e.g., Justiniano and Primiceri, 2008). Khan and Tsoukalas (2011) show the curse still holds within this class of models, and propose reversing it by assuming non-standard preferences that restrict the short-run wealth effects on labor supply as suggested by Jaimovich and Rebelo (2009).[1] Furthermore, if the cost of capital utilization is measured as foregone consumption following Christiano et al. (2005) (CEE), as opposed to increased depreciation of capital as proposed by Greenwood et al. (1988) (GHH), they show that solving the comovement problem will require the complete absence of a wealth effect on labor supply, something which is not supported by their evidence.

By contrast, we propose in this paper reversing the curse without the use of non-standard preferences and a cost of capital utilization measured as capital depreciation. That is, despite standard preferences and a CEE cost of capital utilization, our MSNK model will imply a positive contemporaneous comovement between consumption and investment despite the key role played by investment shocks.

Furthermore, unlike previous work on the comovement problem, we also assess the ability of our model to match the *profiles of cross-correlations* between consumption growth and investment growth, since these provide useful information about the joint dynamics of consumption growth and investment growth.

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[1] Furlanetto and Seneca (2014) also assume non-standard preferences to avoid a short-run fall in consumption following a positive investment shock. They combine sticky prices with Edgeworth complementarity between consumption and hours worked.

We use an approach based on model versions which are simulated numerically, and this to better identify the reasons behind the failures of previous DSGE models with standard preferences and a CEE cost of capital utilization, as well as the key mechanisms driving our new results.

Our framework shares some basic elements of the model developed by Christiano et al. (2005). As such, it includes Calvo (1983) nominal wage and price contracts and real adjustment frictions. However, we extend it along four dimensions. A first dimension is obvious. Unlike Christiano et al. (2005), we consider that business cycle fluctuations are not driven solely by monetary shocks, but also by investment shocks, TFP shocks and risk-premium shocks. To make our case as general as possible, we consider numerical simulations where investment shocks contribute between 40% and 60% of output fluctuations, while adjusting the contribution of TFP shocks accordingly.

The next two dimensions are those which are mostly responsible for the curse reversal. One addition is real per capita output growth stemming from two sources: neutral technology and investment-specific technology. A second addition is firms networking (e.g., Christiano, 2015), or a roundabout production and pricing structure of firms (e.g., Basu, 1995; Huang et al., 2004). With the help of a "Hicksian" decomposition proposed by King (1991) for general equilibrium models, we show that without these additions, the MSNK model can hardly reverse the curse.[2] That is, the MSNK model then delivers a negative contemporaneous correlation between consumption and investment, while implying wrong profiles of cross-correlations.

The Hicksian decomposition disentangles the response of consumption to an investment shock – the source of the anomalous comovements – into a wealth effect and a substitution effect. Without economic growth and firms networking, we show that the problem causing the wrong comovements between consumption and investment is the income effect on consumption which is weakly positive in the wake of a positive investment shock, while the short-run substitution effect is significantly negative. Because on balance the substitution effect dominates the income effect in the short run, the response of consumption is negative on impact of a positive investment shock, remains negative for about six quarters, and then turns positive.

The Hicksian decomposition thus suggests that a potential solution to the comovement problem is to strengthen the positive income effect on consumption, while weakening the negative short-run substitution effect. This is what economic growth and firms networking do in our model. We show that each of these two ingredients boosts the positive income effect on consumption while weakening the negative short-run substitution effect. Of the two, firms networking has the stronger income effect. But taken separately, neither firms networking nor economic growth can generate an income effect which is strong enough and a substitution effect which is weak enough to avoid the

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[2]See also Guerrieri et al. (2014).

negative short-run response of consumption. It is only when both are combined that the response of consumption turns to be non-negative on impact of the positive investment shock and in the following quarters.[3] The contemporaneous comovement between consumption and investment is then positive, and the profiles of their cross-correlations are consistent with the data.

Our fourth addition to CEE' model is to allow trend inflation to be positive. Ascari et al. (2018) have shown that moderate trend inflation can distort key impulse-responses to an investment shock, including the response of consumption, relative to the zero trend inflation case. We show that our main findings are robust to the potential distorting effects of positive trend inflation.

The remainder of the paper is organized as follows. Section 2 lays out our medium-scale DSGE model and discusses some issues related to calibration. Section 3 measures how the standard MSNK model squares with the Barro-King curse. Section 4 adds firms networking and trend output growth to the standard model. Section 5 examines the robustness of our results. Section 6 adds concluding remarks.

2   Models and Calibration

2.1   Standard and Benchmark Models

The standard MSNK model adds investment shocks and non-zero steady-state inflation to the Christiano et al. (2005) model. It includes standard additively separable preferences and a cost of capital utilization measured as foregone consumption. Nominal rigidities take the form Calvo (1983) wage and price contracts. Real adjustment frictions include habit formation in consumption, investment adjustment costs, and variable capital utilization. The monetary authority sets nominal interest rates according to a Taylor rule.

Our benchmark MSNK model adds to the standard MSNK model firms networking (FN) and real per capita output growth (G). Evidence supporting this view of the production and pricing structure of firms is presented in Basu (1995), Huang et al. (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 that covers 473 six-digit 1997 NAICS industries for the years 1959-2009. These data suggest that the share of materials in final sales in the manufacturing sector exceeds 50 percent. For simplicity, we will refer to models incorporating this particular feature as *FN-models*. Models with real per capita output growth will be referred to as *G-models*. Finally, models combining both of these features will be denoted *FN/G*-models.

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[3]Measuring the cost of capital utilization in terms of increased capital depreciation would boost the income effect on consumption even more.

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

Unlike Christiano et al. (2005), the standard and benchmark models abstract from the automatic indexation of non-reset wages and prices to past inflation and/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 the evidence that many wages and prices remain fixed over relatively long periods of time (e.g., Eichenbaum et al., 2011; Klenow and Malin, 2011; Barattieri et al., 2014). Indexation is also criticized for a lack of microeconomic foundations (Chari et al., 2009). Moreover, Cogley and Sbordone (2008) find no evidence of price indexation to the previous period's rate of inflation when sticky prices are used with time-varying trend inflation. Therefore, indexation has recently been omitted from the New Keynesian models of Christiano et al. (2010), Christiano et al. (2015, 2016) and Ascari et al. (2018). FN is able to generate inflation inertia, and this without the unrealistic assumption of backward-looking indexation.

The production function for a typical producer j 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, $\Gamma_t(j)$ denotes intermediate inputs, F is a fixed cost, Υ_t is a growth factor (see below) and production is required to be non-negative. $\phi \in (0, 1)$ is the intermediate input share. Intermediate inputs come from aggregate gross output, X_t. $\widehat{K}_t(j)$ represents capital services measured as the product of utilization (Z_t) and physical capital (K_t), and $L_t(j)$ is the labor input.

The cost minimization problem of a typical firm gives the following expression for the real marginal cost, v_t, which is common to all 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 and w_t is the real wage index. This expression for the 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 economy-wide degree of price stickiness caused by nominal rigidities.

Real per capita output growth stems from trend growth in neutral technology and in investment-specific technology (IST). Greenwood et al. (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 recorded during the postwar period. First, neutral productivity obeys a process with both a trending and stationary component:

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

where 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 stock of physical capital 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 $S(g_I) = S'(g_I) = 0$, and $S''(g_I) > 0$, where $g_I \geq 1$ is the steady state (gross) growth rate of investment. $0 < \delta < 1$ is the depreciation rate of physical capital. $\varepsilon_t^{I,\tau}$ measures the level of IST and enters the capital accumulation equation by multiplying investment.[4] $\varepsilon_t^{I,\tau}$ follows a deterministic trend with no stochastic component. ϑ_t is the investment shock.

Most variables in the model inherit trend growth from the deterministic trends in neutral and investment-specific productivity.[5] 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 firms networking and economic growth in this expression. Without 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 share of intermediate inputs ϕ amplifies the effects of trend growth in neutral productivity on output and

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

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

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.

Our model includes four shocks: a monetary policy shock, an investment shock, a TFP shock, and an intertemporal preference shock. The investment shock ϑ_t in (4) is orthogonal to the relative price of investment goods as in Justiniano et al. (2011). The investment shock follows a stationary AR(1) process, with innovation u_t^I drawn from a mean zero normal distribution with standard deviation s_I:

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

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:

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

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 ε_t^r represents a random deviation from the following Taylor rule:

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

The central bank adjusts the nominal interest rate in response to deviations of inflation from an exogenous steady-state target, and to deviations of output growth from steady state. The monetary policy shock is white noise. The parameter ρ_i governs the degree of smoothing of nominal interest rates, while α_π and α_y determine the Fed's reaction to inflation and output growth.

2.2 Calibration

Tables 1 and 2 summarize the calibration of the model, which is in line with the literature. Appendix B discusses it in further detail. In the text, we focus on the central ingredients of our model which are firms networking, trend output growth, and shocks.

The share of intermediate inputs, ϕ, typically ranges in the literature from 0.5 to 0.8. The cost share of intermediate inputs is equal to the revenue share times the price markup. Nakamura and

Steinsson (2010) 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. Since our calibration implies a steady state markup of 1.2 or 20%, 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, $g_{\varepsilon I}$, 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, to leave out the financial crisis.[6] 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 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.[7]

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 et al. (2011), we set the baseline value of the autoregressive parameter of the investment shock process at 0.8 and that of the intertemporal preference shock at 0.6. In the robustness Section 5, we also look at the effects of lowering the persistence of the investment shock to 0.7 and increasing it to 0.9.

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) assuming an average growth rate of the price index equal to that in the data over the period 1960:I-2007:III. This implies a positive steady-state inflation of 3.52 percent annualized ($\pi^* = 1.0088$).[8]

We then assign to each shock a target percentage contribution to the unconditional variance decomposition of output growth. The key factor in analyzing the Barro-King curse in our New Keynesian settings is the relative contribution of the investment shock to the variance of output

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[6]A detailed explanation of how these data are constructed can be found in Ascari et al. (2018).

[7]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.

[8]Ascari et al. (2018) study the welfare and cyclical implications of moderate trend inflation.

growth relative to the contribution of the TFP shock. In fact, a relative high contribution of the investment shock relative to the TFP shock would make a particular model prone to the curse.

Since the work of Fisher (2006), there have been a number of studies suggesting that investment shocks contribute a large fraction of the variance decomposition of output growth relative to TFP shocks. These studies find that investment shocks explain from 50% to 60% of the variance decomposition of output growth at business cycle frequencies (Justiniano et al., 2010, 2011). TFP shocks explain a significant but smaller fraction of fluctuations in output growth between say 25% and 35%.

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 investment shock, 35 percent to the TFP shock, 8 percent to the intertemporal preference shock, and 7 percent to the monetary policy shock. In the robustness Section 5, we also consider two other different split, varying the relative importance of the investment shock vis-à-vis the TFP shock in contributing to the variance decomposition of output growth. That is, we consider increasing the relative importance of investment shocks by making its contribution 60% and lowering that of TFP shocks to 25%, and lowering its importance by increasing the contribution of TFP shocks to 45% while lowering that of investment shocks to 40%. These different experiments will allow us to analyze the mechanisms that shape the joint dynamics of consumption and investment when the investment shock–the key non-TFP shock–plays a significant role in the model.

Table 3 displays the values of the standard deviations of the shocks generated for the following four model versions. The first column refers to a model with no firms networking (no FN) and no growth (no G), that we name for simplicity "standard MSNK". The second column refers to our benchmark model with firms networking (FN) and growth (G). 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 investment shocks needed to match the actual volatility of output growth are much smaller. The TFP shock is nearly 61% smaller with these features added to the model. FN is the key factor behind the magnifying effects of a TFP shock. With only FN added to the model, the TFP shock is nearly 58% 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 investment shock is 32% 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% 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.

3   Standard MSNK Model

This section addresses the following questions. How does the standard MSNK model square with the stylized facts under our baseline calibration? Is it prone to the curse? If so, what are some potential reasons for this problem?

3.1   Business Cycle Moments

We will focus on moments that help assess whether the standard MSNK model is prone to the Barro-King curse. They include volatility and comovement business cycle statistics. The sample period is 1960:II-2007:III. The variables of interest are output, consumption and investment.

The first row in Table 4 displays moments in the data. Since a model matches the actual volatility of output growth, there is no need to report it in the table. 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 contemporaneous 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 contemporaneous correlation of 0.75. The contemporaneous correlation between the growth rates of consumption and investment is positive and mild in the data at 0.44.

Figure 1 displays the pairwise cross-correlations at lags and leads between the growth rates of output, consumption and investment. The cross-correlations in the data are represented by the lines with circles. These cross-correlations are positive and decreasing in the data, both at lags and leads.

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3.2 Anomalous Comovements

The second row of Table 4 reports some business cycle statistics predicted by the standard MSNK model (i.e., No FN/No G) for our baseline calibration.[9] The standard model somewhat underpredicts the volatility of consumption growth in the data at 0.44 compared to 0.47, but significantly overstates the volatility of investment growth by 23 percent and the volatility of hours by 25 percent.

The standard model fails to match key business cycle comovements. One such failure is predicting a negative contemporaneous correlation between the growth rates of consumption and investment at -0.05 relative to 0.44 in the data. Furthermore, it implies incorrect patterns of cross-correlations between consumption growth and investment growth. That is, the cross-correlations at lags and leads of 1 to 4 quarters implied by the standard model and denoted by the solid lines in Figure 1 are more or less flat around zero, contrasting with the substantially positive and decreasing pattern of cross-correlations in the data.

The contemporaneous correlation between consumption growth and output growth implied by the standard model is mildly positive at 0.39 relative to 0.75 in the data. The cross-correlations between consumption growth and output growth in the standard model are also systematically lower than those in the data.

What explains these anomalies in the standard MSNK model? The anomalies are related to how consumption adjusts in response to an investment shock. As shown by the dotted line in the second panel of the first row of Figure 2, a positive investment shock is followed by a short-run decline of consumption before the response turns positive. The investment 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 investment shock, the rate of return is higher and investment is more profitable, so agents substitute consumption for investment. The impulse-response function of consumption is hump-shaped, so consumption drops on impact, keeps decreasing for two quarters, and then starts increasing, only turning above steady state after six quarters.

3.3 Hicksian Decomposition

One way to convey some intuition for the failures of the standard MSNK model is by considering the "Hicksian" decomposition proposed by King (1991) for general equilibrium models. Figure 3 decomposes the response of consumption (hours) to a positive investment shock into a wealth effect

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

and a substitution effect. The wealth effect on consumption is defined as the log change in steady-state consumption that would yield the same change in intertemporal utility as that generated by the investment shock keeping prices, wages and the real interest rate constant at their steady state levels. The substitution effect is the path of consumption that would induce no change in utility in reaction to price, wage and interest rate changes induced by the investment shock.

The wealth and substitution effects for consumption and hours implied by the standard MSNK model are represented by dotted lines in the four panels of Figure 3. As evidenced by these figures, the problem of the standard model is that it implies a weak positive income effect on consumption and a strong negative short-run substitution effect on consumption. On balance, the short-run negative substitution effect dominates the positive wealth effect on consumption, implying that the response of consumption to a positive investment shock is negative for quite some time.

4   Reversing the Curse

This section examines how adding firms networking (FN) and economic growth (G) impacts moments vis-à-vis the standard model. The moments from our benchmark MSNK model are reported in Table 4. This table shows that our benchmark model almost exactly matches the volatilities of consumption growth, investment growth, and the log first difference in hours worked.

With both FN and G, the contemporaneous correlation between the growth rates of consumption and investment turns out to be positive at 0.36, not far from the actual correlation which is 0.44. The contemporaneous correlation between consumption growth and output growth also rises substantially, now being 0.7 compared to 0.75 in the data.

Another significant improvement with the benchmark model is that it broadly reproduces the profiles of the cross-correlations between the growth rates of consumption and investment, and the growth rates of consumption and output. The cross-correlations implied by the benchmark model are those denoted by the dashed lines in Figure 1. Note how well it reproduces the profiles of cross-correlations which are positive and decreasing in the data compared to the patterns predicted by the standard model which is more or less flat around zero.

The benchmark model also closely matches the positive and decreasing cross-correlations between consumption growth and output growth at both lags and leads, compared to the standard model which systematically understates these cross-correlations at all lags and leads.

The key behind our new findings is that our benchmark model delivers a positive response of consumption following a positive investment shock, as shown by the solid line in the second panel

of the first row of Figure 2. That is, consumption rises on impact of a positive investment shock and it continues to increase over time.

Of course, the main question now is: How does the benchmark model generate a positive response of consumption to a positive investment shock? 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. 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.

As a result, the higher path of output creates a stronger income effect on consumption in our model. This can be seen from Figure 3 where we use the Hicksian decomposition proposed by King (1991). There, we can see that the income effect on consumption induced by the investment 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 MSNK model is too weak 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 MSNK model with FN and growth makes the key macroeconomic variables (i.e., output, consumption, investment and hours) positively comove after an investment shock. As such, it reverses the Barro-King curse that only TFP shocks are able to generate the typical positive comovements between these variables. It actually goes further than surviving the Barro-King curse, as it also quite closely matches the cross-correlations between cosnsumption growth and investment growth, and consumption growth and output growth.

4.1 Disentangling the Effects of FN and Trend Growth

Next, we disentangle the effect of FN and trend output growth on our findings. Table 4 reports the unconditional moments implied by the following two versions of the model: one with output

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

growth but no FN (No FN/Growth), and the other with FN but no trend output growth (FN/No Growth).[11]

The table shows that trend output growth and FN each leads to some improvements in business cycle comovements relative to the standard MSNK model. For instance, the contemporaneous correlation between the growth rates of consumption and investment becomes weakly positive with either one of these features added to the standard model. Therefore, adding either one of these features represents a step in the right direction. 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 an investment shock relative 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 an investment 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 six 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 MSNK 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.

5   Checking for Robustness

Now, one may ask how varying the relative contribution of investment and TFP shocks in some reasonable range would affect the relative performance of our standard and benchmark MSNK models? Furthermore, since the investment shock is the source of the anomalous comovement between consumption growth and investment growth one can also ask how making the investment

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[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.

shock more or les persistent than in our baseline would affect our results in the two models? This subsection offers answers to these questions.

5.1 Relative Size of Shocks

We consider two different scenarios determining the relative importance of shocks. A first scenario, we call Split 1, increases the importance of the investment shock relative to the TFP shock by raising its contribution to 60% and lowering the contribution of the TFP shock to 25%. These percentage contributions correspond exactly to the estimates reported by Justiniano et al. (2011) for these two shocks. A second scenario, or Split 2, increases the contribution of the TFP shock to 45% while lowering that of the investment shock to 40%. The contributions for the other two types of shocks are kept constant. The numerical values for the shock standard deviations corresponding to both scenarios are reported in Table 5.

Table 6 replicates Table 4 showing selected business cycle moments for both splits. With the investment shock contributing 60% of the variance decomposition of output growth, the standard MSNK model predicts that the contemporaneous correlation between the growth rates of consumption and investment, and that between the growth rates of consumption and output are more distant from the actual correlations than with our baseline calibration. The correlation between consumption growth and investment growth implied by the standard model is now -0.16 compared to 0.44 in the data. Meanwhile the correlation between consumption growth and output growth is 0.26 compared to 0.75 in the data.

The benchmark model with firms networking and economic growth still performs well with a more important investment shock. That is, the correlation between the growth rates of consumption and investment is 0.3, while the correlation between the growth rates of consumption and output is 0.65.

With a TFP shock that contributes to 45% of the variance of output growth and the investment shock to only 40%, both the standard and benchmark models increase their ability to match the contemporaneous correlations between the growth rates of consumption and investment, and the the growth of consumption and output. This is not surprising since with a less important investment shock there is less of an effect on the rate of return of investment, and thus a lower incentive to invest more and postpone consumption for the future. In fact, in this particular case, our benchmark model matches both of these correlations almost exactly.

Therefore, with an alternative split of shocks, our benchmark model systematically outperforms the standard MSNK model in terms of its ability to replicate the correlation between consumption growth and investment growth and the correlation between consumption growth and output growth.

Similarly to Figure 1, Figure 4 shows the cross-correlations for our baseline calibration and for the two alternative splits of shocks. It demonstrates that the results from our benchmark model are quite robust to the changes in the relative importance of shocks. Intuitively, the cross-correlograms from our benchmark calibration are between the ones generated from Splits 1 and 2. The alternative splits have some effects on the cross-correlations, but these effects are relatively small.

5.2 Persistence of the Investment Shock

We now assess the sensitivity of our results to varying the degree of persistence of the investment shock. Table 7 shows how selected business cycle moments change with ρ_I taking a lower value (0.7) or a higher value (0.9). With a less persistent investment shock, the key correlations which have been the object of our special attention improve in both models. With a more persistent investment shock, the opposite occurs as the performance of the models deteriorates. This is particularly true for the correlation between consumption growth and investment growth in the standard model that becomes quite negative at -0.43. By comparison, in our benchmark model this correlation remains positive but is lower at 0.09.

6 Conclusion

The recent literature shows that medium-scale New Keynesian models, with monopolistic competition in the goods and labor markets, sticky wages and sticky prices have been empirically successful. In several multi-shock New Keynesian models, investment shocks are typically identified as the main driving force behind business cycle fluctuations. We show that these models are vulnerable to the Barro-King curse with several anomalous business cycle comovements, especially where consumption is involved, because an improvement in the marginal efficiency of investment typically triggers a short-run contractionary effect on consumption.

We have proposed a way for the MSNK model to survive the curse. Our alternative approach is based on two empirically relevant features: roundabout production and trend output growth stemming from trend growth in neutral technology and investment-specific technology. We think our approach is more general in that it does not require non-standard preferences that restrict the strength of short-run wealth effects on the labor supply. It is also general enough to escape the curse whether the cost of capital utilization is measured in terms of increased depreciation of capital or foregone consumption. We view these refinements as increasing the empirical plausibility of this class of models and their usefulness for policy analysis.

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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 et al. (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 et al. 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 et al. 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:

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

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.[12] ϑ_t is a stochastic investment 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:

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[12]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:

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

$$\text{s.t.}$$

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

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:

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

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

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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 investment 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 et al., 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 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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.[13] 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 et al. (2005), but can be viewed as conservative in light of the evidence in Eichenbaum et al. (2011) and Klenow and Malin (2011) suggesting that prices remain fixed for relatively long periods of time.[14] The average frequency of wage adjustments is somewhat lower than suggested by the estimates in Christiano et al. (2005), but higher than implied by the estimates in Justiniano, Primiceri and Tambalotti (2010, 2011) and Barattieri et al. (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.

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[13]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.

[14]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.[15] 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.

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[15]A detailed explanation of how these data are constructed can be found in Ascari et al. (2018).

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

Shocks	Alternative Models			
	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 investment 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.

Table 4: Moments in the benchmark and standard MSNK models

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$
Data	(0.0047)	(0.0202)	(0.0079)
Standard MSNK	0.0044	0.0264	0.0105
Benchmark	0.0048	0.0194	0.0078
No FN / Growth	0.0045	0.0217	0.0098
FN / No Growth	0.0045	0.0240	0.0084

	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$
Data	**(0.7542)**	(0.9192)	**(0.4362)**
Standard MSNK	**0.3889**	0.8892	**-0.0481**
Benchmark	**0.7030**	0.9021	**0.3562**
No FN/ Growth	0.5262	0.8933	0.1256
FN / No Growth	0.5840	0.8999	0.1941

Note: this table shows selected moments generated from the Standard MSNK 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 investment 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 investment 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

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$
Data	(0.0047)	(0.0202)	(0.0079)
Standard MSNK	0.0042	0.0281	0.0100
Benchmark	0.0045	0.0205	0.0073
No FN / Growth	0.0042	0.0231	0.0093
FN / No Growth	0.0042	0.0254	0.0079
	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$
Data	**(0.7542)**	(0.9192)	**(0.4362)**
Standard MSNK	**0.2610**	0.9003	**-0.1628**
Benchmark	**0.6458**	0.9117	**0.3001**
No FN/ Growth	0.4266	0.9035	0.0303
FN / No Growth	0.4957	0.9098	0.1090

Panel B: Split 2

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$
Data	(0.0047)	(0.0202)	(0.0079)
Standard MSNK	0.0046	0.0246	0.0111
Benchmark	0.0051	0.0181	0.0083
No FN / Growth	0.0047	0.0203	0.0103
FN / No Growth	0.0048	0.0224	0.0090
	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$
Data	**(0.7542)**	(0.9192)	**(0.4362)**
Standard MSNK	**0.5075**	0.8806	**0.0720**
Benchmark	**0.7561**	0.8949	**0.4176**
No FN/ Growth	0.6173	0.8856	0.2248
FN / No Growth	0.6641	0.8925	0.2822

Note: this table shows selected moments generated from the Standard MSNK 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 investment 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 investment 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 investment shock

Panel A: $\rho_I = 0.7$

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$
Data	(0.0047)	(0.0202)	(0.0079)
Standard MSNK	0.0042	0.0244	0.0105
Benchmark	0.0048	0.0189	0.0078

	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$
Data	**(0.7542)**	(0.9192)	**(0.4362)**
Standard MSNK	**0.5148**	0.9011	**0.1215**
Benchmark	**0.7302**	0.9067	**0.4019**

Panel B: $\rho_I = 0.9$

	$\sigma(\Delta C)$	$\sigma(\Delta I)$	$\sigma(\Delta L)$
Data	(0.0047)	(0.0202)	(0.0079)
Standard MSNK	0.0058	0.0328	0.0105
Benchmark	0.0052	0.0222	0.0078

|	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta C, \Delta I)$
Data	**(0.7542)**	(0.9192)	**(0.4362)**
Standard MSNK	**0.0869**	0.8517	**-0.4256**
Benchmark	**0.5332**	0.8746	**0.0871**

Note: this table shows selected moments generated from the Standard MSNK 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.

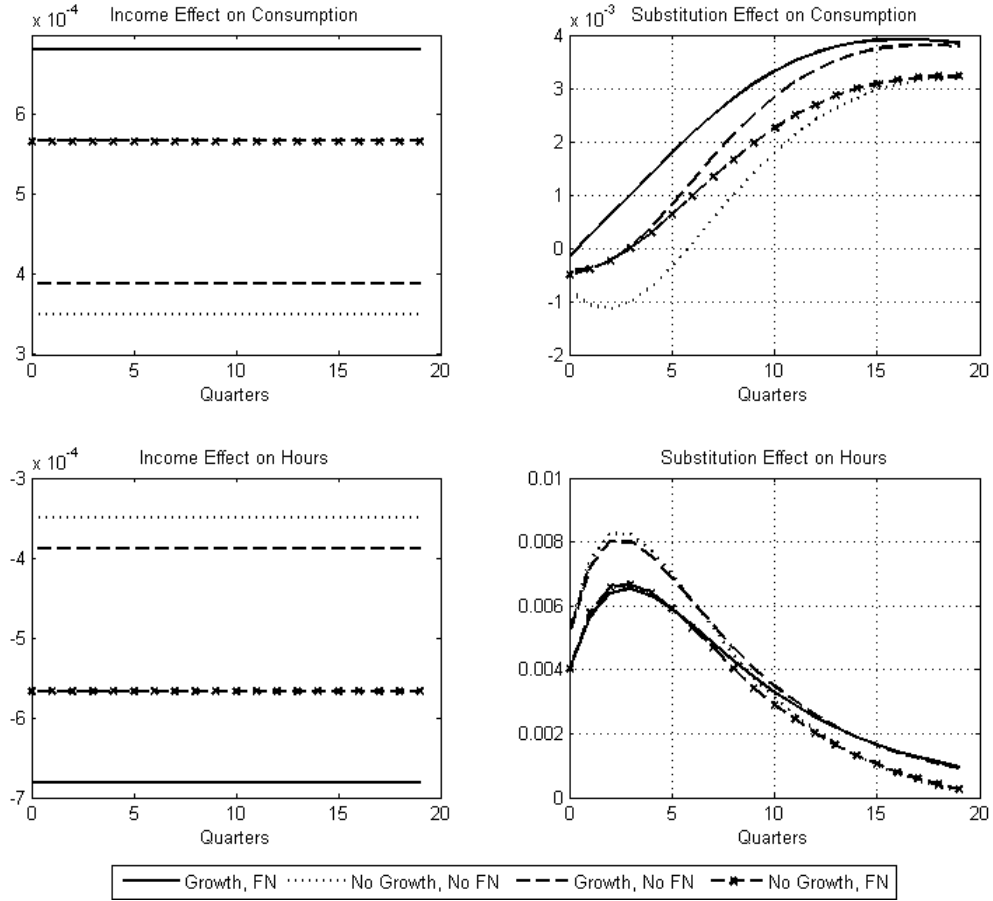Figure 1: Cross-correlogram of the key macroeconomic variables in the benchmark model
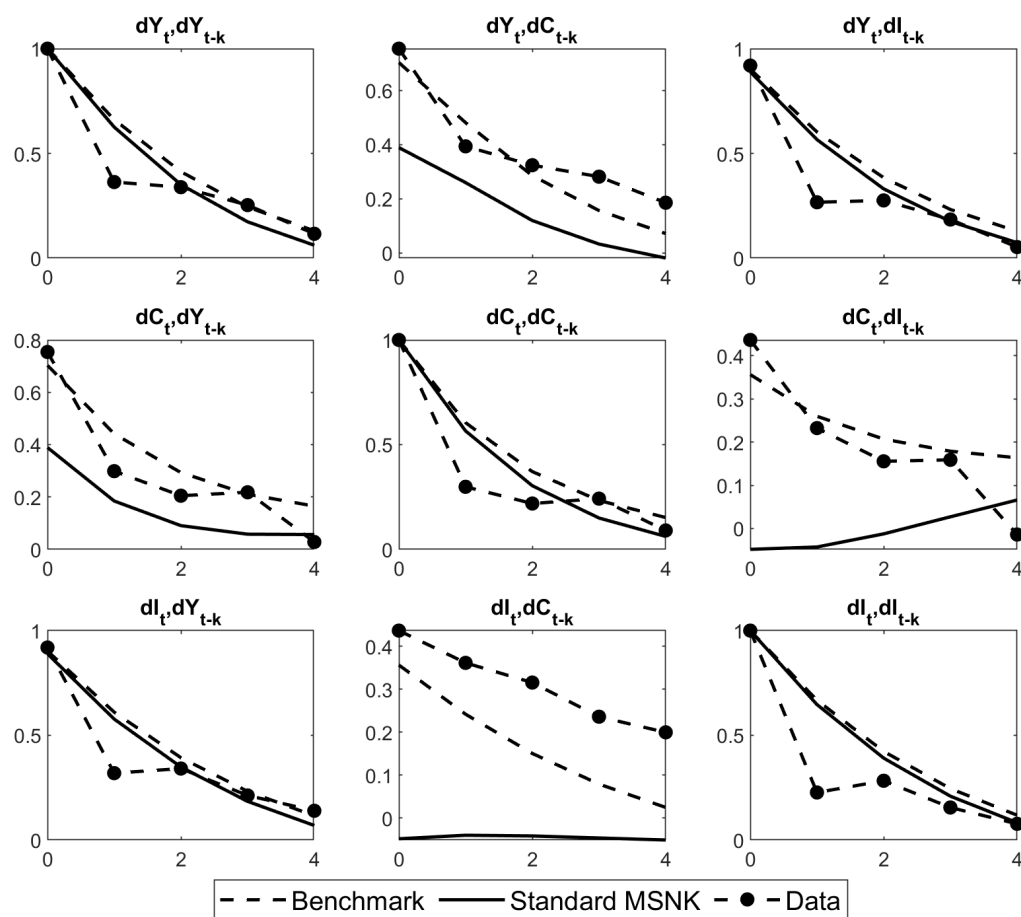
Note: this figure plots the cross-correlations of output, consumption, and investment growth rates in the data, in the benchmark (FN/G) model and in the Standard MSNK (No FN/No G) one, for our benchmark calibration: the investment shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent.

Figure 2: Impulse responses to the investment shock
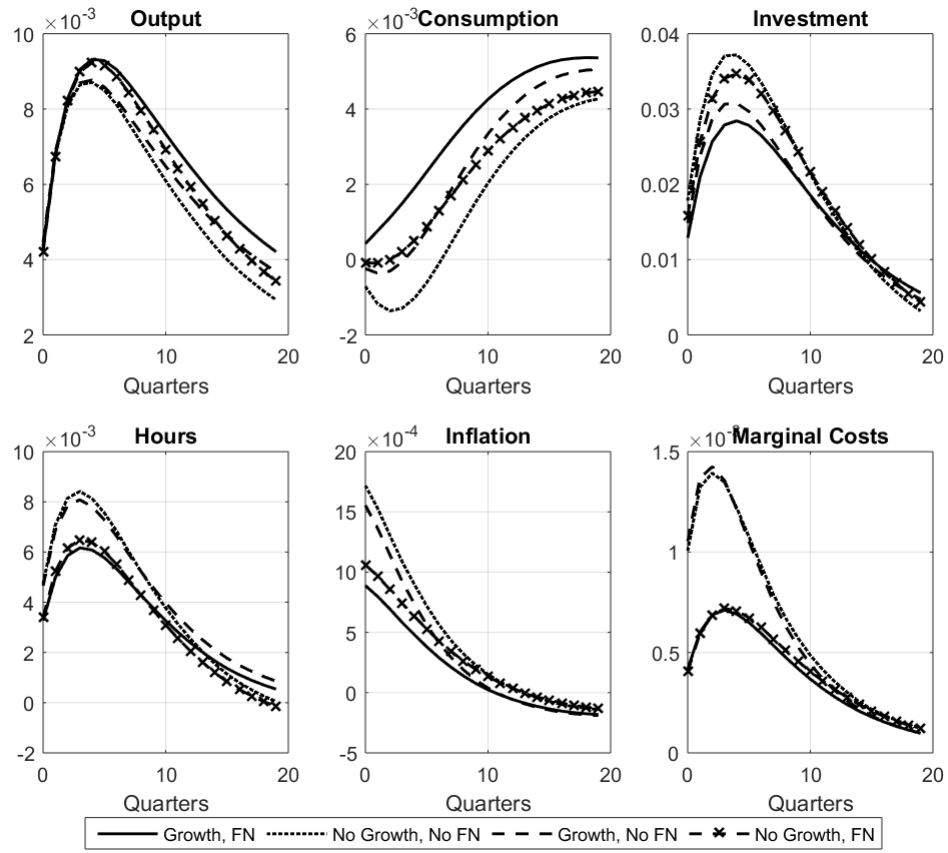
Note: this figure plots the impulse response of output, consumption, investment, hours, inflation and marginal costs for our benchmark calibration: the investment shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 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 MSNK 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 MSNK 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: Cross-correlations of the key macroeconomic variables in the benchmark model for alternative splits
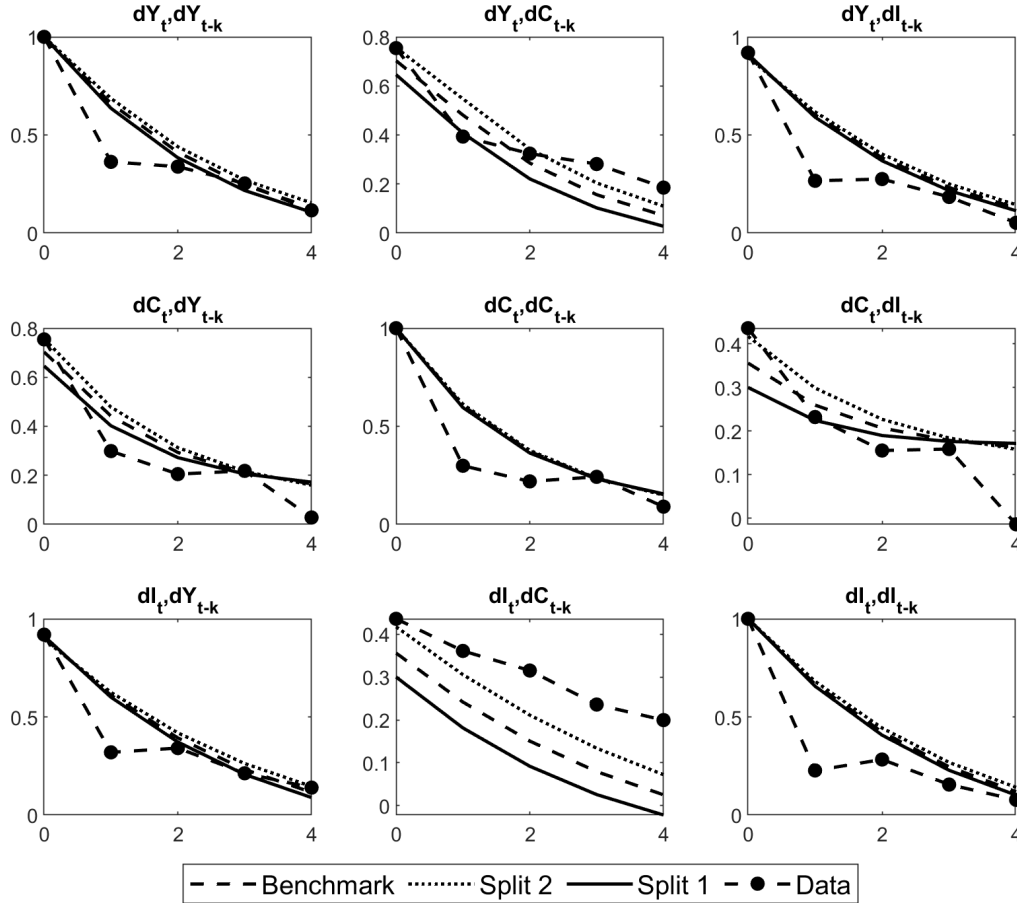
Note: this figure plots the cross-correlations of output, consumption, and investment growth rates for our benchmark calibration for alternative splits. Benchmark: the investment shock accounts for 50 percent of the variance of output growth, the neutral technology shock for 35 percent, the monetary policy shock for 7 percent, and the preference shock for 8 percent. Split 1: the investment 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 investment 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.