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Production Stages and the Transmission of Technological Progress

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Abstract:
We develop and estimate a DSGE model which realistically assumes that many goods in the economy are produced through more than one stage of production. Firms produce differentiated goods at an intermediate stage and a final stage, post different prices at both stages, and face stage-specific technological change. Wage-setting households are imperfectly competitive with respect to labor skills. Intermediate-stage technology shocks explain most of short-run output fluctuations, whereas final-stage technology shocks only have a small impact. Despite the dominance of technology shocks, the model predicts a near-zero correlation between hours worked and the return to work and mildly procyclical real wages. The factors mainly responsible for these findings are an input-output linkage between firms operating at the different stages and movements in the relative price of goods. We show that, depending the source, a technology improvement may either have a contractionary or expansionary impact on employment.

Keywords: Business Cycles, Production Stages, Technological Change, Nominal Rigidities

JEL Classification: E32

1 Introduction

The empirical identification of the underlying forces that cause business cycles is a leading topic of research in macroeconomics. In a series of influential articles based on neoclassical theory, shocks to total factor productivity (TFP) are considered to be the major source of short-run aggregate fluctuations (e.g., Kydland and Prescott, 1982; Hansen, 1985; Prescott, 1986). However, a recent literature claims that technology shocks are mostly irrelevant for postwar business cycles (e.g., Galí, 1999; Christiano, Eichenbaum and Vigfusson, 2004; Basu, Fernald and Kimball, 2006).[1] For instance, Hall (1997) forcefully argues that real business cycle (RBC) models, emphasizing the importance of technology shocks and intertemporal mechanisms, must be called into question. He presents suggestive evidence that random shifts in household preferences, rather than exogenous variations in the pace of technology, are the main factors driving postwar business cycles. While sharing Hall's (1997) scepticism about the relevance of standard RBC models for the analysis of short-run fluctuations, the present paper proposes a new explanation of the transmission of technological progress and offers new evidence of the importance to technology shocks for the understanding of business cycles.

Most optimization-based macroeconomic models assume that firms operate at the finished-good processing stage for which technological change matters only at the final stage of production. However, several goods in the economy are typically produced through more than one processing stage, while firms at different stages in the processing chain charge different prices for the goods they produce. Considering this reality prompts some potentially important questions about the propagation of technological change. Can exogenous variations in the pace of technology during intermediate stages of production have an impact on the business cycle? If so, is it quantitatively important? If technology shocks are found to be an important source of short-run fluctuations in a model featuring a multi-stage production and pricing structure, can this structure also contribute to remedy anomalies that have plagued a large class of models wherein technology shocks are the dominant source of business-cycle fluctuations? Based on a dynamic stochastic general equilibrium (DSGE) model embedding a two-stage production and pricing structure, and estimated on U.S. postwar quarterly data, our paper answers affirmatively to all these questions.

For the purpose of our investigation, we construct a DSGE model of the postwar U.S. business cycle that incorporates the following main structural components: i) price-setting monopolistic competitors that produce differentiated goods both at an intermediate stage and a final stage, ii)

[1] However, Fisher (2006) provides evidence suggesting that investment-specific rather than neutral technology shocks matter for the business cycle.

exogenous variations in the pace of technology which are specific to each processing stage, iii) an interconnection between firms modeled by the use of intermediate goods as productive inputs by firms engaged in the production of finished goods, iv) allocative movements in the relative price of goods, v) wage-setting monopolistic households with differentiated labor skills, vi) some real frictions in the form of costs incurred by increasing the stock of aggregate physical capital and by varying the quantity of the labor input at each processing stage, vii) a monetary authority that sets short-term interest rates according to a Taylor-type rule, and viii) structural shocks to preferences, technology at different stages, and monetary policy. The model is estimated over the postwar U.S. period with econometric techniques similar to those in Ireland (2004a,b).

The evidence in Basu (1995) and Huang, Liu and Phaneuf (2004) establishes that the interaction between nominal rigidities and a roundabout input-output structure may significantly alter the transmission of monetary shocks.[2] However, while these models assume that firms are related through a *horizontal* roundabout input-output structure within a *single* final stage of production, our model postulates that firms are linked *vertically,* across processing stages. Hence, our framework is closer in spirit to a class of models featuring production chains such as Blanchard (1983) and Huang and Liu (2001, 2005).[3] Furthermore, given the recent controversy on the relevance of technology shocks for short-run fluctuations, our paper takes a closer look at the effects of stage-specific technological change on the postwar business cycle rather than focusing on the effects of monetary shocks only.

A first set of substantive findings can be summarized as follows. The two-stage production and pricing model is strongly supported by the data. Some key structural parameters of the model, including the share of intermediate goods into the production of finished goods as well as the parameters determining the length of nominal contracts and the importance of the real frictions are estimated to be statistically significant and economically meaningful. According to the variance decompositions for a variety of forecast horizons obtained from our estimated two-stage model, the

[2] Basu (1995) shows that a demand-driven model with intermediate inputs and sticky prices accounts for procyclical productivity, while predicting large welfare losses from monetary nonneutrality. Huang et al. (2004) show that such a model with intermediate inputs, nominal wage rigidity and nominal price rigidity is able to capture the switch in the cyclicality of real wages observed from the interwar to the postwar period even when aggregate fluctuations are driven only by monetary shocks.

[3] Blanchard (1983) studies the impact of a production chain structure on price level inertia, goods early in the chain having more flexible prices than goods further down the chain. Huang and Liu (2001) propose a DGE model that stresses the role of production chains in the transmission of monetary shocks. Using a calibrated model, Huang and Liu (2005) assume an input-output linkage between sectors to analyze the design of optimal monetary policy with several sources of nominal price rigidities.

intermediate-stage technology shock accounts for the bulk of postwar fluctuations, contributing to 52 and 70 percent of the four and twenty quarter ahead cyclical variance of output, respectively. Furthermore, we find that the intermediate-stage technology shock is the main source of cyclical movements in intermediate-stage and final-stage hours. Meanwhile, the final-stage technology shock explains only a small fraction of the cyclical variance in output–less than 10 percent over an horizon of four to twenty quarters, a finding which is broadly consistent with the evidence reported by other researchers with somewhat different approaches (e.g., Galí, 1999; Christiano et al., 2004; Basu et al., 2006). The preference shock plays a minor role over all horizons. The policy shock has a substantial impact on the variance of output over a very short horizon, explaining 51 and 36 percent, respectively, of the one and four quarter ahead variability in output, but its effect rapidly declines as the horizon increases. However, it feeds more than 70 percent of the variance in finished-good inflation over all horizons, while technology shocks of all stages explain between 20 and 25 percent of the variability in finished-good inflation once their effects are combined.

We propose an explanation as to why the intermediate-stage technology shock has such a strong impact on short-run fluctuations while its final-stage counterpart does not. Consider first a technological improvement at the intermediate stage of production. Our estimated model predicts that this type of shock will give rise to a persistent drop in intermediate-good inflation and to a sharp, persistent decline in the relative price of intermediate goods. The fall in the relative price of intermediate goods has principally two effects. First, it exerts a forceful upward pressure on the demand for intermediate goods, leading to a strong increase in the demand for labor and capital inputs at the intermediate stage and to higher income for the household. With higher income, consumption, investment, and the households' demand for the final good rise. Second, as intermediate goods become relatively less expensive, firms use more intermediate inputs in the production of finished goods, which further raises final output. Overall, a positive intermediate-stage technology shock drives output and employment up along the production chain, generating a boom in output and hours at all stages.

The mechanisms are very different when technology improves at the final stage. Both finished-good inflation and the relative price of finished goods fall. However, for this case, our estimated model reveals that the decline in the relative price of finished goods is both smaller and less persistent than the fall in the relative price of intermediate goods that follows an intermediate-stage technology improvement, except for the period immediately after the shock. Hence, the upward pressure on the demand for finished goods is not appreciable. Furthermore, the rise in the relative price of intermediate goods lowers the demand for this type of good. Both intermediate-stage output and hours fall. Final-stage firms use less intermediate goods to produce their output. Overall, the increase in the demand for final output is not strong enough to keep up with the rise in final-stage productivity, so that final-stage hours will fall.

Working with a one-stage model, Galí (1999) shows that an exogenous increase in multifactor productivity may lead to a short-run fall in employment as long as nominal prices are sticky and monetary policy is weakly accommodative (see also Basu, Fernald and Kimball, 2006). In contrast with the standard sticky-price model, our two-stage model has startlingly different implications for the adjustment of hours depending on the source of technological change. First, it predicts a strong and positive comovement between hours and output which is typical of postwar business cycles in response to an intermediate-stage technology improvement. Second, it also implies a short-run decline in hours worked in response to a final-stage technology improvement. However, as our paper shows, the short-run decline in hours following a positive final-stage technology shock is mostly driven by movements in the relative price of goods and by the interconnectedness of firms at various stages, not by sticky prices and a weakly accommodative monetary policy. Still, our paper shows that the new keynesian features of the model play a key role in our main findings.

A second set of substantive results concerns our model's ability to overcome some well known anomalies encountered in a wide range of business cycle models characterized by technology shocks as the dominant source of fluctuations. For example, the estimated two-stage model dramatically improves on the performance of canonical, one-stage real business cycle models. Kydland and Prescott (1982), for instance, argue that a successful model should explain "why...the consumption of market produced goods and the consumption of leisure move in opposite directions in the absence of any apparent large movement in the real wage" (p.1360), while "cyclical employment fluctuates substantially more than productivity does" (p.1367). The two-stage model does very well along these particular dimensions of the data, predicting ratios of the volatility of the average productivity of labor to output, hours to productivity and real wages to output that are close to those found in the data.

Furthermore, despite the dominance of technology shocks as a source of short-run fluctuations, the two-stage model successfully passes Christiano and Eichenbaum's (1992) "litmus test for macroeconomic models" (p.430), predicting a near-zero correlation between hours worked and the average productivity of labor.[4] Hansen and Wright (1992) have shown that a large class of RBC

[4]This is also known in the literature as the Dunlop-Tarshis observation. Stated literally, the Dunlop-Tarshis observation is the fact that real wages have been more or less acyclical during the interwar period rather than strongly countercyclical. Christiano and Eichenbaum (1992) interpret the near-zero correlation between hours and productivity as the modern reincarnation of the Dunlop-Tarshis observation.

models fails to explain this critical comovement, predicting a correlation between hours and productivity which is high and positive. Also, the two-stage model correctly predicts that real wages are mildly procyclical, while they usually are strongly procyclical in RBC models.

To improve the correlation between hours and productivity, Christiano and Eichenbaum (1992) suggest adding measurable economic impulses that possibly shift the labor supply function to an otherwise standard RBC model with indivisible labor. They incorporate shocks to government consumption and find that the correlation between hours and the return to work can be reduced to 0.575. Pushing this line of research further, Braun (1994) and McGrattan (1994) include disturbances in labor and capital tax rates, in addition to government consumption shocks.[5] Contrasting sharply with these models, the two-stage model does not have to rely on variables that may potentially shift the labor supply function to correctly predict labor market dynamics. With hours rising when technology improves at the intermediate stage, the correlation between hours and productivity conditional on this shock is positive. Because hours fall following a positive final-stage technology shock, the correlation between hours and productivity produced by this shock is negative. Thus, on balance, the two-stage model predicts a near-zero correlation between hours and the return to work even when it is conditional only on technology shocks.

The two-stage model also has interesting implications for price dynamics. One finds in the early work of Means (1935) the observation that the nominal prices of goods early in the production chain are significantly more volatile than the prices of goods further down the chain of production (see also the evidence in Gordon, 1981, Blanchard, 1987, Clark, 1999 and Hanes, 1999). Such evidence also motivates the work of Blanchard (1983).[6] The two-stage model predicts that the variability in intermediate-stage inflation is nearly two times larger than variability in final-stage inflation, which seems broadly consistent with the evidence we report later in the paper.

To shed some light on our model's main driving mechanism, we estimate two variants of our general framework. The first assumes that firms produce only finished goods and still features sticky nominal wages and real frictions, but only one source of nominal price rigidity. The second incorporates the two-stage production structure and real frictions, but with fully flexible nominal wages and prices. This variant can be interpreted as a two-stage RBC model. On the basis of formal likelihood ratio tests, we provide evidence that the general framework cannot be rejected in favor of each of the variants. The one-stage model with nominal rigidities predicts highly countercyclical

[5] Adding some real frictions like habit formation in consumption and investment adjustment costs to a RBC model can possibly reverse the sign of the correlation between hours and productivity, making it strongly negative as hours may decline following a positive technology shock (e.g., Francis and Ramey, 2005).

[6] See also Huang and Liu (2001).

real wages and a strong, negative correlation between hours and productivity. The two-stage RBC model, like standard one-stage RBC models, predicts highly procyclical real wages and a strong, positive correlation between hours and productivity.

The paper is organized as follows. Section 2 describes the two-stage model with nominal rigidities and real frictions. Section 3 discusses some estimation issues. Section 4 presents and analyzes our main findings. Section 5 offers concluding remarks.

2 A Model with a Two-Stage Production and Pricing Structure

The economy is inhabited by a large number of infinitely lived households endowed with differentiated labor skills. Each household has preferences defined over expected streams of consumption goods, real balances and leisure. Utility is additively separable in leisure. Preferences are subject to a shock that shifts the marginal utility of goods and real balances consumption. A competitive firm aggregates households' labor into a composite labor input employed by two sets of producers. At the intermediate stage, intermediate goods are produced by a continuum of price-setting monopolistic competitors using capital and labor. These goods are CES-aggregated by a perfectly competitive firm to yield a composite intermediate input. At the final stage, the composite intermediate input is used, alongside capital and labor, by a continuum of price-setting monopolistic competitors to produce finished goods. These goods are CES-aggregated by a perfectly competitive firm to yield a final good. The timing of all price setting and wage setting decisions is exogenous in the spirit of Calvo (1983). Households must pay a cost to adjust the aggregate stock of physical capital. It is also costly to vary hours worked at each stage. In each period, capital is perfectly mobile across firms and is rented by finished-good and intermediate-good producers after observing all shocks. Technology shocks affect the productivity of producers at each stage. The monetary authority sets the nominal interest rate based on a Taylor-type rule, which also subject to stochastic innovations.

2.1 Households

Assume a continuum of households, each endowed with a differentiated skill indexed by $i \in [0, 1]$. The household $i \in [0, 1]$ has a utility function:

$$E \sum_{t=0}^{\infty} \beta^t \left[\frac{\gamma}{\gamma - 1} \kappa_t \log \left(C_t(i)^{\frac{\gamma-1}{\gamma}} + b^{\frac{1}{\gamma}} \left(\frac{M_t(i)}{P_{y,t}} \right)^{\frac{\gamma-1}{\gamma}} \right) - \mu \frac{N_t(i)^{1+\eta}}{1+\eta} \right], \tag{1}$$

where E is an expectations operator, $\beta \in (0, 1)$ is a subjective discount factor, $C_t(i)$ is real consumption, $M_t(i)/P_{y,t}$ is real money balances, $P_{y,t}$ is the price index for finished goods, and $N_t(i)$

denotes hours worked; γ, b, μ and η are positive structural parameters, with γ representing the constant elasticity of substitution between consumption and real balances, and η the inverse of the elasticity of labor supply. The representative household's total time available is normalized to one in each period.

The preference shock, κ_t, has the following time-series representation:

$$\log(\kappa_t) = \rho_\kappa \log(\kappa_{t-1}) + \varepsilon_{\kappa,t}, \tag{2}$$

where $\varepsilon_{\kappa,t}$ is a serially uncorrelated independent and identically distributed process with mean-zero, and standard error σ_κ (see also Hall, 1997, Galí and Rabanal, 2004 and Ireland, 2004a).

Household $i \in [0, 1]$ faces the budget constraint

$$\begin{aligned} & C_t(i) + I_t(i) + CAC_t(i) + \frac{M_t(i)}{P_{y,t}} + \frac{B_{t+1}(i)}{P_{y,t}} \\ = \; & \frac{W_t(i)}{P_{y,t}} N_t(i) + \frac{Q_t}{P_{y,t}} K_t(i) + \frac{M_{t-1}(i)}{P_{y,t}} + R_{t-1} \frac{B_t(i)}{P_{y,t}} + \frac{D_{y,t}(i)}{P_{y,t}} + \frac{D_{z,t}(i)}{P_{y,t}} + \frac{T_t(i)}{P_{y,t}}, \end{aligned} \tag{3}$$

where $I_t(i)$ is investment, $CAC_t(i)$ represents the cost households have to pay to adjust the aggregate stock of physical capital $K_t(i)$, $B_{t+1}(i)$ stands for the bonds carried by the household into period $t+1$, $W_t(i)$ is the nominal wage rate, Q_t is the nominal rental rate of capital, R_{t-1} is the gross nominal interest rate between period $t-1$ and period t, $D_{y,t}(i)$ denotes the nominal dividends paid to the household by firms operating at the final stage, $D_{z,t}(i)$ represents the nominal dividends paid by firms producing at the intermediate stage, and $T_t(i)$ is a lump-sum nominal transfer from the monetary authority.

The cost $CAC_t(i)$ is determined by the function:

$$CAC_t(i) = \frac{\varphi_k}{2} \left(\frac{K_{t+1}(i)}{K_t(i)} - 1 \right)^2 K_t(i), \tag{4}$$

where $\varphi_k > 0$.

The investment technology is

$$I_t(i) = K_{t+1}(i) - (1 - \delta) K_t(i), \tag{5}$$

where $\delta \in (0, 1)$ is the rate of depreciation of physical capital.

The aggregate labor input, N_t, is a composite of all labor skills,

$$N_t = \left(\int_0^1 N_t(i)^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}}, \tag{6}$$

where σ is the elasticity of substitution between skills. The demand function for labor skill i is

$$N_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\sigma} N_t, \tag{7}$$

where the wage rate W_t of the composite skill is related to the wage rates of the differentiated skills by

$$W_t = \left(\int_0^1 W_t(i)^{1-\sigma} di\right)^{\frac{1}{1-\sigma}}. \tag{8}$$

The household i chooses $C_t(i)$, $M_t(i)$, $B_{t+1}(i)$, $K_{t+1}(i)$ and $W_t(i)$ (when the household can adjust the nominal wage) which maximize the expected discounted sum of utility flows, subject to the budget constraint and the firms' labor demand for skill i.

2.1.1 Wage Contract

In each period, the nominal wage rate can be adjusted with probability $1 - d_w$. The first-order condition with respect to $W_t(i)$ determines the following nominal wage contract

$$\widetilde{W}_t(i) = \frac{\sigma}{\sigma - 1} \frac{E_t \sum_{q=0}^{\infty} (\beta d_w)^q N_{t+q}(i)^{\eta+1}}{E_t \sum_{q=0}^{\infty} (\beta d_w)^q N_{t+q}(i) \lambda_{t+q}(i) \frac{1}{P_{y,t+q}}}, \tag{9}$$

where $\lambda_t(i)$ is the nonnegative Lagrange multiplier associated with the budget constraint. At the symmetric equilibrium, the aggregate nominal wage is given by the following recursive equation:

$$W_t = \left[d_w W_{t-1}^{1-\sigma} + (1 - d_w) \widetilde{W}_t^{1-\sigma}\right]^{\frac{1}{1-\sigma}}, \tag{10}$$

where $\widetilde{W}_t$ is the average wage of the households allowed to revise their nominal wages in period t.

2.2 Firms in the Two-Stage Production Structure

Firms at the intermediate and final stages are related by an input-output linkage. Monopolistically competitive producers set nominal prices at each stage. In any given period, the price of finished goods can be adjusted with probability $1 - d_y$, and the prices of intermediate goods with probability $1 - d_z$.

2.2.1 Final Stage of Production

Final-stage output Y_t is a composite of all the finished goods $Y_t(j)$, $j \in (0, 1)$ denoting a particular type of finished good,

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{\theta_y - 1}{\theta_y}} dj \right)^{\frac{\theta_y}{\theta_y - 1}},$$

where θ_y is the elasticity of substitution between finished goods.

The firm producing finished good j solves the following profit maximization problem:

$$\max_{Y_t(j)} P_{y,t} \left(\int_0^1 Y_t(j)^{\frac{\theta_y - 1}{\theta_y}} dj \right)^{\frac{\theta_y}{\theta_y - 1}} - \int_0^1 P_{y,t}(j) Y_t(j) dj,$$

where $P_{y,t}(j)$ is the price of good j. The demand function for this type of good is

$$Y_t(j) = \left(\frac{P_{y,t}(j)}{P_{y,t}} \right)^{-\theta_y} Y_t, \tag{11}$$

where the price index for the finished goods $P_{y,t}$ is given by

$$P_{y,t} = \left(\int_0^1 P_{y,t}(j)^{1-\theta_y} dj \right)^{\frac{1}{1-\theta_y}}.$$

2.2.2 Intermediate Stage of Production

Intermediate-stage output Z_t is a composite of all the intermediate goods $Z_t(l)$, $l \in (0,1)$ denoting a particular type of intermediate good,

$$Z_t = \left(\int_0^1 Z_t(l)^{\frac{\theta_z - 1}{\theta_z}} dl \right)^{\frac{\theta_z}{\theta_z - 1}},$$

where θ_z is the elasticity of substitution between intermediate goods.

The demand function for the intermediate good l is

$$Z_t(l) = \left(\frac{P_{z,t}(l)}{P_{z,t}} \right)^{-\theta_z} Z_t, \tag{12}$$

where $P_{z,t}(l)$ is the price of good l. The price index for the intermediate goods $P_{z,t}$ is

$$P_{z,t} = \left(\int_0^1 P_{z,t}(l)^{1-\theta_z} dl \right)^{\frac{1}{1-\theta_z}}.$$

2.2.3 Firms at the Final Stage

Producing finished good j requires the use of labor $N_{y,t}(j)$, capital $K_{y,t}(j)$, and intermediate goods $Z_t(j)$. Finished-good j is produced through the following constant returns to scale technology:

$$Y_t(j) = Z_t(j)^{\phi} \left[A_{y,t} K_{y,t}(j)^{\alpha_y} N_{y,t}(j)^{1-\alpha_y} \right]^{1-\phi}, \tag{13}$$

where ϕ, $\alpha_y \in (0,1)$.

The final-stage technology shock $A_{y,t}$ follows the stochastic process

$$\log(A_{y,t}) = (1-\rho_{A_y}) \log(A_y) + \rho_{A_y} \log(A_{y,t-1}) + \varepsilon_{y,t}, \tag{14}$$

where $\varepsilon_{y,t}$ is a serially uncorrelated independent and identically distributed process with mean-zero, and standard error σ_y

Each firm j must pay a cost to vary hours worked. This cost is determined by the following function:

$$LAC_{y,t}(j) = \frac{\varphi_y}{2} \left(\frac{N_{y,t}(j)}{N_{y,t-1}(j)} - 1 \right)^2 Y_t,$$

where $\varphi_y > 0$.

Firms at the final stage are price-takers in the markets for inputs. The firm producing finished good j solves the following problem :

$$\max_{\{K_{y,t}(j), N_{y,t}(j), Z_t(j), P_{y,t}(j)\}} E_t \sum_{q=0}^{\infty} (\beta d_y)^q \frac{\lambda_{t+q}}{\lambda_t} \frac{D_{y,t+q}(j)}{P_{y,t+q}},$$

subject to:

$$D_{y,t}(j) = P_{y,t}(j) Y_t(j) - Q_t K_{y,t}(j) - W_t N_{y,t}(j) - P_{z,t} Z_t(j) - P_{y,t} LAC_{y,t}(j),$$

and equations (11) and (13).

2.2.4 Price Decisions at the Final Stage

The first-order condition for $P_{y,t}(j)$ determines the contract for the price of finished good j

$$\tilde{P}_{y,t}(j) = \frac{\theta_y}{\theta_y - 1} \frac{E_t \sum_{q=0}^{\infty} (\beta d_y)^q \frac{\lambda_{t+q}}{\lambda_t} \zeta_{y,t}(j) Y_{t+q}(j)}{E_t \sum_{q=0}^{\infty} (\beta d_y)^q \frac{\lambda_{t+q}}{\lambda_t} Y_{t+q}(j) \frac{1}{P_{y,t+q}}}, \tag{15}$$

where $\zeta_{y,t}(j)$ is the real marginal cost of the firm producing finished good j.

At the symmetric equilibrium, the average price of finished goods is

$$P_{y,t} = \left[d_y P_{y,t-1}^{1-\theta_y} + (1-d_y) \tilde{P}_{y,t}^{1-\theta_y} \right]^{\frac{1}{1-\theta_y}}, \tag{16}$$

where $\tilde{P}_{y,t}$ is the average price of firms at the final stage allowed to revise their prices in period t.

2.2.5 Firms at the Intermediate Stage

The intermediate-stage firm l rents capital $K_{z,t}(l)$ and hires workers $N_{z,t}(l)$ to produce the intermediate good $Z_t(l)$ with the following production technology:

$$Z_t(l) = A_{z,t} K_{z,t}(l)^{\alpha_z} N_{z,t}(l)^{1-\alpha_z}, \tag{17}$$

where $\alpha_z \in (0,1)$.

The intermediate-stage technology shock $A_{z,t}$ is generated by the following stochastic process

$$\log(A_{z,t}) = (1-\rho_{A_z}) \log(A_z) + \rho_{A_z} \log(A_{z,t-1}) + \varepsilon_{z,t}, \tag{18}$$

where $\varepsilon_{z,t}$ is a mean–zero, i.i.d. normal process with standard error σ_{A_z}.

Intermediate-stage firm l must pay a cost to vary hours worked. This cost is determined by the following function:

$$LAC_{z,t}(l) = \frac{\varphi_z}{2} \left(\frac{N_{z,t}(l)}{N_{z,t-1}(l)} - 1 \right)^2 Z_t,$$

where $\varphi_z > 0$.

Firm l solves the profit maximization problem

$$\max_{\{K_{z,t}(l), N_{z,t}(l), P_{z,t}(l)\}} E_t \sum_{q=0}^{\infty} (\beta d_z)^q \frac{\lambda_{t+q}}{\lambda_t} \frac{D_{z,t+q}(l)}{P_{y,t+q}},$$

subject to:

$$D_{z,t}(l) = P_{z,t}(l) Z_t(l) - Q_t K_{z,t}(l) - W_t N_{z,t}(l) - P_{z,t} LAC_{z,t}(l),$$

and equations (12) and (17).

2.2.6 Price Decisions at the Intermediate Stage

The first-order condition for $P_{z,t}(l)$ determines the contract for the price of intermediate good l

$$\tilde{P}_{z,t}(l) = \frac{\theta_z}{\theta_z - 1} \frac{E_t \sum_{q=0}^{\infty} (\beta d_z)^q \frac{\lambda_{t+q}}{\lambda_t} \zeta_{z,t}(l) Z_{t+q}(l)}{E_t \sum_{q=0}^{\infty} (\beta d_z)^q \frac{\lambda_{t+q}}{\lambda_t} Z_{t+q}(l) \frac{1}{P_{z,t+l}}}, \tag{19}$$

where $\zeta_{z,t}(l)$ is the real marginal cost of the firm producing intermediate good l. At the symmetric equilibrium, the average price of the intermediate goods is given by

$$P_{z,t} = \left[d_z P_{z,t-1}^{1-\theta_z} + (1-d_z)\tilde{P}_{z,t}^{1-\theta_z} \right]^{\frac{1}{1-\theta_z}}, \tag{20}$$

where $\tilde{P}_{z,t}$ is the average price of firms at the intermediate stage allowed to revise their prices in period t.

2.3 The Monetary Policy Rule

The central bank sets the nominal interest rate R_t in response to deviations of finished-good inflation $\pi_{y,t}$ and final-stage output Y_t from their respective steady-state values π_y^* and Y^*. Furthermore, following Rotemberg and Woodford (1999) and Clarida, Galí and Gertler (2000), the monetary authority can smooth nominal interest rates. The rule also includes a serially correlated policy shock. Some authors have questioned whether the lagged interest rate is a fundamental component of the policy rule. They argue that it may simply reflect serially correlated policy errors or the Fed's reaction to factors not included in the rule (see for example Rudebusch, 2002, and English, Nelson and Sack, 2003). Hence, our specification is:

$$\log\left(\frac{R_t}{R^*}\right) = \rho_R \log\left(\frac{R_{t-1}}{R^*}\right) + (1-\rho_R)\left[\rho_\pi \log\left(\frac{\pi_{y,t}}{\pi_y^*}\right) + \rho_y \log\left(\frac{Y_t}{Y^*}\right)\right] + v_t, \tag{21}$$

where

$$v_t = \rho_v v_{t-1} + \varepsilon_{v,t}, \tag{22}$$

R^* is the steady-state gross nominal rate of interest, and $\varepsilon_{v,t}$ is a serially uncorrelated independent and identically distributed process with mean-zero, and standard error σ_v.

2.4 Closing the Model

The market-clearing conditions at the symmetric equilibrium are:

$$K_t = K_{y,t} + K_{z,t}, \tag{23}$$

where $K_{y,t} = \int K_{y,t}(j)dj$ and $K_{z,t} = \int K_{z,t}(l)dl$,

$$N_t = N_{y,t} + N_{z,t}, \tag{24}$$

where $N_{y,t} = \int N_{y,t}(j)dj$ and $N_{z,t} = \int N_{z,t}(l)dl$,

$$Y_t = C_t + I_t + CAC_t + LAC_{y,t} + LAC_{z,t}, \tag{25}$$

and

$$M_t - M_{t-1} = T_t. \tag{26}$$

The bond market clearing condition implies that

$$B_t = 0 \text{ for all } t. \tag{27}$$

2.5 Equilibrium

An equilibrium consists of allocations $C_t(i)$, $B_t(i)$, $M_t(i)$, $I_t(i)$, $K_{t+1}(i)$, and the nominal wage $W_t(i)$ for the household $i \in [0,1]$; allocations $Y_t(j)$, $K_{y,t}(j)$, $N_{y,t}(j)$, and the price $P_{y,t}(j)$ for the finished-good producer $j \in [0,1]$; allocations $Z_t(l)$, $K_{z,t}(l)$, $N_{z,t}(l)$, and the price $P_{z,t}(l)$ for the intermediate-good producer $l \in [0,1]$; together with prices $P_{y,t}$, $P_{z,t}$, R_t, and the nominal wage W_t that satisfy the following conditions: (i) the household's allocations solve its utility maximization problem; (ii) each finished-good producer's allocations and price solve its profit maximization problem taking the other prices and nominal wages as given; (iii) each intermediate-good producer's allocations and price solve its profit maximization problem; (iv) the markets for bonds, money, and the composite goods clear; and (v) the monetary policy is described by the rule (21).

As in Rotemberg and Woodford (1997), we assume the existence of state contingent securities ensuring that, in equilibrium, households are homogeneous with respect to consumption and asset holdings, whereas they are heterogeneous with respect to the wage rate and labor supply.

3 Econometric Procedure

3.1 Estimation

The model is solved by log-linearizing its equilibrium conditions around a symmetric steady state in which all variables are constant. The linearized system yields the following state space representation:

$$\mathcal{X}_t = \mathbf{A}\mathcal{X}_{t-1} + \mathbf{B}\epsilon_t, \tag{28}$$

$$\mathcal{Y}_t = \mathbf{C}\mathcal{X}_t, \tag{29}$$

where $\mathcal{X}_t$ is a vector that includes the model's predetermined and exogenous variables and $\mathcal{Y}_t$ is a vector composed of the remaining endogenous variables. The likelihood function $\mathcal{L}(Y^T|\Theta)$ associated with the state-space solution is evaluated using the Kalman filter. Prior to the estimation, we define the following vector of observables:

$$\mathcal{Z}_t = \begin{bmatrix} \hat{c}_t & \widehat{y}_t & \widehat{R}_t & \hat{\pi}_{y,t} & \hat{y}_t - \hat{n}_t & \hat{w}_t \end{bmatrix}',$$

which includes real consumption, final output, the nominal interest rate, finished-good inflation, the average productivity of labor, and the real wages, each variable being measured in percentage-deviations from its steady-state value.

Since the model is estimated using these six time-series, while it contains four structural shocks, we append two shocks representing measurement errors (see also Altug, 1989, Sargent, 1989, and Ireland, 2004b). The system of equations for the selected variables is

$$\mathcal{Z}_t = \mathbf{K} \begin{pmatrix} \mathcal{X}_t \\ \mathcal{Y}_t \end{pmatrix} + \mathbf{L} \begin{pmatrix} \epsilon_t \\ e_t \end{pmatrix}, \tag{30}$$

where $\mathbf{K}$ and $\mathbf{L}$ are matrices which are obtained after choosing the appropriate variables in $\mathcal{X}_t$, $\mathcal{Y}_t$, and the vector of errors. The measurement errors, that we assume to be independent from the structural shocks, follow the autoregressive process:

$$e_{t+1} = \mathbf{M} e_t + \upsilon_t, \tag{31}$$

$$E\left(\upsilon_t \upsilon_t'\right) = \Sigma_\upsilon, \tag{32}$$

where $\mathbf{M}$ and Σ_υ are diagonal matrices.

3.2 Data

We use U.S. quarterly time series for the period 1960:I to 2004:IV. The nominal interest rate is measured by the Three-month Treasury Bill Rate. The rate of inflation of finished goods is the quarterly rate of change of the consumer price index. Real consumption is the sum of consumption expenditures on nondurable goods and services. Output is the sum of total personal consumption expenditures and private fixed investment. The real wage is the ratio of the nonfarm business sector compensation to the consumer price index. Hours worked are the total hours in the nonfarm business sector. All series, except the nominal interest rate, are seasonally adjusted. Consumption, output and hours worked are converted into per capita terms after being divided by the civilian population aged 16 years and over. Also, all series, except the nominal interest rate and the rate of inflation, are logged and detrended using the Hodrick-Prescott filter.

3.3 Calibration

When estimating relatively large structural models using maximum likelihood techniques, it is sometimes difficult to obtain sensible estimates of all the structural parameters either because some parameters are not easy to identify or because the optimization algorithm fails to locate the maximum due the complexity of the objective function. This issue can be alleviated by calibrating some parameters prior to the estimation. First, the subjective discount factor β is set to 0.995, which implies a steady-state annual real interest rate of 2 percent. The parameter μ, measuring the weight on leisure in the utility function, is such that the representative household devotes approximately one third of its time to work in the steady state. The rate of depreciation of physical capital is set at 0.025. The parameters θ_y and θ_z, determining the steady-state markups of finished-good and intermediate-good prices over their respective marginal costs, both take a value of 8, implying a steady-state markup of 14 percent at each stage (see also Basu, 1995 and Huang, Liu and Phaneuf, 2004).[7] The elasticity of substitution between differentiated labor skills σ is 6.0, and is thus consistent with the microeconomic evidence provided by Griffin (1992) and the evidence from aggregate time series reported in Ambler, Guay and Phaneuf (2006).

4 Empirical Results

4.1 The Benchmark Model

The *benchmark model* is one that includes the complete list of structural ingredients described in section 2. In that case, the set of structural parameters that we seek to estimate is summarized by $\{\rho_{A_z}, \rho_{A_y}, \rho_{\kappa}, \rho_{\upsilon},\ \sigma_{A_z}, \sigma_{A_y}, \sigma_{\kappa}, \sigma_{\upsilon}, b, \gamma, \eta, \alpha_z, \phi, \alpha_y, d_z, d_y, d_w, \varphi_k, \varphi_z, \varphi_y, \rho_R, \rho_\pi, \rho_y\}$. Table 1 reports the point estimates of the structural parameters with their standard deviations.

The shocks to preferences and intermediate-stage technology are the most persistent with AR(1) coefficients of 0.95 and 0.96, respectively; they are followed by the shock to final-stage technology with $\rho_{A_y} = 0.87$ and by the shock to the policy rule with $\rho_\upsilon = 0.16$. Of these four shocks, the

[7]Basu and Fernald (2002) find that the steady-state markup is about 5 percent when factor utilization rates are controlled for, while it is about 12 percent without correction for factor utilization. The value proposed by Rotemberg and Woodford (1997) is 20 percent without correction for factor utilization.

policy shock has the largest standard deviation with $\sigma_\upsilon = 0.023$, followed by the intermediate-stage technology shock with $\sigma_{A,z} = 0.0197$, the final-stage technology shock with $\sigma_{A,y} = 0.0181$, and the preference shock with $\sigma_\kappa = 0.0133$. Hence, it is worth noting that the intermediate-stage technology shock is more persistent and has a slightly larger standard deviation than its final-stage counterpart.

The point estimate $\gamma = 0.0701$ implies an interest elasticity of money demand of -0.0754, consistent with the evidence reported in Ireland (2003) and Kim (2000). The parameter b determining the relative importance of consumption and real balances in preferences is 0.0744. The point estimate $\eta = 0.8831$ implies an elasticity of labor supply of 1.13, consistent with the evidence reported in Mulligan (1998).

The probability that the prices of finished goods stay put in any given period is 0.6561, while for intermediate goods it is 0.6992. These probabilities imply that the prices of finished goods are reoptimized once every 2.9 quarters on average, while the prices of intermediate goods are revised once every 3.3 quarters. In comparison, the evidence in Christiano, Eichenbaum and Evans (2005) says that firms change their prices once every 2.5 quarters on average, whereas according to the evidence in Galí and Gertler (1999) they adjust their prices once every 6 quarters.[8] The microeconomic evidence offered by Bils and Klenow (2004) tells that firms revise their prices somewhat more frequently than our estimates suggest.[9] Wage contracts last 6.5 quarters on average.[10]

The share of physical capital into the production of intermediate goods α_z is 0.3407, while the share of capital into the production of finished goods α_y is 0.13. Both estimates imply a share of hours which is approximately two thirds at each stage. The point estimate of the share of intermediate inputs into the production of finished goods ϕ is 0.2416. This estimate could seem a little bit low considering that Basu (1995) assigns to the share of intermediate inputs a value of 0.5. However, it is difficult to draw a direct comparison between our estimate and the calibration in Basu (1995) for the following reasons. First, Basu (1995) works in the context of a one-stage model with nominal price rigidity and without capital accumulation. His model is thus very different from ours. Second, his ϕ-value is taken from a study by Jorgenson, Gollop and Fraumeni (1987) that covers the period 1947 to 1979. Furthermore, their study does not rely on a fully articulated

[8] Their evidence is obtained from one-stage models.

[9] It is difficult to make a direct comparison between our findings and those of Bils and Klenow (2004), as they examine the frequency of price changes for 350 categories of goods and services covering about 70 percent of consumer spending between the years 1995 and 1997.

[10] Smets and Wouters (2005) report a point estimate of the Calvo-probability for nominal wage contracts of about 0.8 or 0.89 depending on the particular postwar U.S. sample they choose.

optimization-based model. In contrast, our sample period is much longer (1960:I to 2004:IV) and our estimate is obtained using a full-blown two-stage DSGE model. Third, the analysis in Jorgenson et al. (1987) is limited to the U.S. manufacturing sector. The manufacturing industry certainly uses a greater share of intermediate inputs than many other sectors do. For example, this share is much smaller in the trade and financial services sectors.

The parameter φ_k determining aggregate capital-adjustment cost is 9.5827. The labor-adjustment-cost parameter is 5.7406 at the final stage and 3.3746 at the intermediate stage.

The point estimate of ρ_π in the policy rule is 1.4702, close to the value of 1.5 proposed by Taylor (1993). The estimate of ρ_y is not far from zero. We do not find evidence of strong interest-rate smoothing with an estimate of ρ_R of 0.0918.

4.2 Sources of Short-Run Fluctuations

What are the most important shocks for short-run fluctuations? Table 2 reports the variance decompositions at the infinite horizon for several variables based on our estimated benchmark model. Over the infinite horizon, the intermediate-stage technology shock is by far the most important, contributing to 72.3 percent of the variance of final output, 67 percent of the variance of consumption, 80.7 percent of the variance of investment and 44.9 percent of the variance of total hours. It also explains 84.2 percent of the variance of intermediate-stage output and 76.2 percent of the variance of intermediate-stage hours. Note that the intermediate-stage technology shock is also the main source of the variability in final-stage hours, contributing to 37.4 percent of its variance. In contrast, the final-stage technology shock is not very important, contributing to 5.1 percent of the variance of final output, 4.8 percent of the variance of consumption, and 5.3 percent of the variance of investment. This shock, however, explains a somewhat larger fraction of the variability in employment, with 19.6 percent of the variance of total hours worked. The policy shock is the most important determinant of the variability in inflation, feeding 71.6 percent of the variance of finished-good inflation and 89.5 percent of the volatility of intermediate-good inflation. Combining their effects, the two technology shocks explain a non negligible 25 percent of the variability in finished-good inflation. The preference shock only has a small effect on the variance of most variables.

Table 3 focuses on the variance decompositions of Y_t, Z_t, $\pi_{y,t}$ and $\pi_{z,t}$ for a broader range of forecast horizons. The intermediate-stage technology shock is the main force that drives business cycles, explaining as much as 52.1 percent, 62.3 percent, 65.7 percent and 68 percent, respectively, of the four-, eight-, twelve-, and twenty-quarter ahead forecast error variance of final output. Meanwhile, the final-stage technology shock explains only a small percentage–less than 10 percent–of the variance of final output at the same horizons, a finding which is broadly consistent with the evidence reported by other researchers using SVAR models (Galí, 1999; Christiano, Eichenbaum and Vigfusson, 2004). The policy shock contributes quite substantially to output fluctuations at the one-quarter ahead forecast horizon–50.7 percent–but this percentage rapidly declines as the horizon increases. The policy shock is also the most important source of variability in inflation at all horizons. Preference shocks have a negligible effect on the variances of output and inflation.

4.3 The Effects of Stage-Specific Technological Change

We now examine the dynamic effects of stage-specific technological change in the benchmark model. Figure 1 displays several impulse responses to a one percent intermediate-stage technology shock. A positive intermediate-stage technology shock is followed by a sharp, persistent decline in the relative price of intermediate goods p_z; the relative price p_z initially drops by 0.3 percent, continues to fall during several quarters before reaching a maximum decline of 1.7 percent after fifteen quarters, and remains 1 percent below its pre-shock level forty quarters after the shock. With p_z falling, the demand for intermediate goods rises strongly and persistently, inducing a strong, persistent increase in the demand for labor and capital inputs at the intermediate stage, and leading to higher income for the households. With a higher income, the households' demand for final output rises, further raising the demand for intermediate inputs and primary factors. Firms producing finished goods also use more intermediate inputs. Thus, an intermediate-stage technology shock generates a strong increase in final output. Note also that the intermediate-stage technology shock produces typical hump-shaped responses in final output, consumption, investment and total hours, hence meeting the criterion of a model evaluation suggested by Cogley and Nason (1995).

The dynamic responses of prices after an intermediate-stage technology shock are different at the two stages. A positive intermediate-stage technology shock has a direct impact on the real marginal cost of firms producing intermediate goods, generating a persistent decline in the rate of inflation of intermediate goods. In contrast, the rate of inflation of finished goods rises by 0.22 percent on impact due to the strong expansion in final-stage output.

The effects of a positive final-stage technology shock are summarized in Figure 2. The relative price of finished goods falls (or p_z rises). However, the effect on p_z is both significantly smaller (in absolute value) and less persistent than the effect generated by an intermediate-stage technology shock. Therefore, the upward pressure exerted by this type of shock on the demand for finished goods is not very strong, so final output weakly rises. Also, because of the rise in the relative price of intermediate goods, firms producing finished goods use less intermediate goods to produce. Thus, given the relatively weak pressure on the demand for finished goods and less intermediate inputs used in the production of finished goods, the rise in the demand for final output cannot keep up with the increase in final-stage productivity, so final-stage hours have to fall. Furthermore, because p_z rises, the demand for intermediate goods falls, leading to a decline in intermediate-stage hours and output. A final-stage technology improvement is therefore followed by a decline in hours worked at both stages.

Overall, an intermediate-stage positive technology shock has a much stronger expansionary impact than its final-stage counterpart. Also, a key feature of the two-stage model is that a technology improvement may either have an expansionary or contractionary impact on employment depending on the source of technological change.

4.4 Business Cycle Statistics

One way to assess the performance of our benchmark model is to look at its ability to match a fairly comprehensive set of stylized facts. Table 4 compares business-cycle statistics taken from the data with those predicted by the estimated model. The time series are detrended using the Hodrick-Prescott filter.

The estimated benchmark model provides a good match on several dimensions of the data. In particular, it has interesting implications for the dynamics of the labor market. As mentioned earlier, an important strand of literature has focused on two stylized facts observed during the postwar period: i) hours worked have fluctuated a lot more than the average productivity of labor (e.g., Kydland and Prescott, 1982; Hansen, 1985) and ii) the correlation between hours and productivity has been close to zero (e.g., Christiano and Eichenbaum, 1992; Hansen and Wright, 1992; Braun, 1994; McGrattan, 1994). The model accounts very well for these facts. First, it predicts that the volatility of hours is 1.86 times larger than that of productivity, while it is 1.76 times larger in the data. Second, the correlation between hours and productivity in the benchmark model is -0.116, while according to the data it is -0.053.

Models in which technology shocks are assumed to be the dominant source of short-run fluctuations usually predict a strong positive correlation between hours and productivity. To better understand the reasons of this improvement, we decompose the correlation between hours and productivity conditional on the type of shock causing it in the benchmark model. The results are presented in Table 5. When driven only by the intermediate-stage technology shock, the correlation between hours and productivity is 0.506, while it is -0.83 conditional on the final-stage technology shock. Combining the effects of both technology shocks, this correlation becomes −0.02, which is very close to the unconditional correlation found in the data. This finding follows directly from the model's implications concerning the response of hours worked following a technology improvement, hours rising when technology improves at the intermediate stage and declining when the technology improvement takes place at the final stage. Thus, unlike other types of models that have been proposed in the literature before (e.g., Christiano and Eichenbaum, 1992; Braun, 1994; McGrattan, 1994), the two-stage model does not have to rely on disturbances that shift the labor-supply function to provide a better match of the correlation between hours and productivity.

The benchmark model also does well in reproducing the relative volatility of hours and output, predicting a ratio of 0.928 compared to 0.854 in the data. At the same time, it does not imply that real wages are excessively volatile relative to output. We conclude that the two-stage model is able to take up the challenge of Kydland and Prescott (1982), as hours worked fluctuate significantly more than productivity without generating excessively large variations in real wages.

Note also that the benchmark model predicts that real wages are mildly procyclical, which is also in agreement with available evidence. Models in which technology shocks play a major role usually predict that real wages are strongly procyclical. One reason why the benchmark model does well along this particular dimension is that it implies a mildly positive correlation between real wages and output conditional on both technology shocks. The model predicts that the technology-driven correlation between real wages and output is 0.52, which is not too far from the unconditional correlation of 0.372 found in the data. The mildly positive correlation between real wages and output in the face of technology shocks can be explained as follows. First, real wages are weakly countercyclical following a final-stage technology shock. As seen before, when technology improves at the final stage, final output rises during 3-4 quarters, and then begins to fall during several quarters. This observed pattern in the dynamic response of final output mostly reflects the negative hump-shaped responses of final-stage hours and intermediate goods following a final-stage technology improvement. Second, real wages are quite procyclical in response to an intermediate-stage technology shock. So, on balance, real wages are mildly procyclical conditional on both technology shocks. After taking into account the effects of aggregate demand shocks, the correlation between real wages and output in the benchmark model is 0.247.

We look next at the behavior of nominal prices in the benchmark model. Following Huang and Liu (2005), we measure finished-good inflation and intermediate-good inflation by CPI-inflation and PPI-inflation, respectively. The benchmark model matches very well the relative volatility of both inflation rates and the comovement between these two rates. The ratio of the volatility of

CPI-inflation to PPI-inflation found in the data is 0.475, whereas in the benchmark model the ratio of the variability in finished-good inflation to intermediate-good inflation is 0.554. The comovement between these rates in the data is 0.75 and 0.805 in the model.

4.4.1 Sensitivity Analysis

This section identifies the most important factors behind our main results. We first look at the role of the input-output linkage by assuming that the parameter ϕ takes an arbitrarily small value, while the rest of parameters in the benchmark model remains the same. Figure 3 looks at several impulse responses following an intermediate-stage shock and a final-stage technology shock, respectively. With a very small share of intermediate inputs, firms producing finished goods are almost completely insulated from the intermediate stage. A positive intermediate-stage technology shock generates a sharp decline in the relative price of intermediate goods and a very strong increase in intermediate-stage hours and output. However, the boom in intermediate-stage output is weakly transmitted to the final stage, firms producing finished goods making almost no use of intermediate inputs. Hence, the increase in final output is much smaller without the input-output linkage. Meanwhile, the effects of final-stage technology shocks on final output, total hours, consumption and investment are almost unaffected by this change.

Galí (1999), in the context of a one-stage model with sticky nominal prices, argues that nominal price rigidity and a weakly accommodative monetary policy are two factors that may have a major impact on the short-run response of employment following a technology improvement. Figure 4 looks at the role of sticky nominal prices in the benchmark model by assuming that the prices of finished goods and intermediate goods are both reoptimized in each period ($d_y = d_z = 0$). Assuming that nominal prices are perfectly flexible at both stages has a minor impact on the results, as the relative prices of goods are not very affected by the changes in d_y and d_z. Hence, although nominal prices are revised in each period, employment continues to fall following a final-stage technology improvement, while it still rises when technology improves at the intermediate stage.

One possible concern is that the smaller effects of a final-stage technology shock on final output may be driven by the smaller persistence found in the stochastic process generating this type of shock relative to the persistence found in the process for the intermediate-stage technology shock. Indeed, we saw that the AR(1) coefficient estimated for the final-stage technology shock is 0.87, while it is 0.96 for the AR(1) coefficient of the intermediate-stage technology shock. Figure 5 conveys two types of information. First, it looks at the responses of final output, consumption, investment, final-stage hours and total hours following a positive final-technology shock for different values of ρ_{A_y} (0.75 and 0.96). With a higher AR(1) coefficient, the final-stage technology shock generates a short-run increase in consumption, investment and output, but the effect on final output is not very strong. The second element of information is perhaps more interesting. Here, we assign an arbitrarily small value to the share of intermediate inputs into the production of finished goods, while assuming different values for ρ_{A_y}. When $\rho_{A_y} = 0.96$ and final-stage firms do not use intermediate inputs to produce, a final-stage technology improvement generates a strong, positive, hump-shaped response in final output, consumption and investment. A positive final-stage technology shock now induces a positive, hump-shaped, short-run increase in final-stage and total hours worked. This finding also confirms the important role played by the input-output linkage in the benchmark model.

4.5 Alternative Models

Another way to assess our model's main driving mechanism is to estimate some model's variants and compare their results with those of the benchmark model. We label *Model I*, a model featuring only one stage of production, thus excluding the two-stage production and pricing structure and the input-output linkage between stages. This model is estimated after imposing the following parameter restrictions: $\{\rho_{A,z} = \sigma_{A,z} = \alpha_z = \phi = d_z = \varphi_z = 0\}$. It is driven by three structural shocks only, as the intermediate-stage technology shock is now omitted from the model. Model I is similar to existing new keynesian models.

Model II, on the other hand, combines the two-stage production structure, while assuming that firms reoptimize their prices and households revise their nominal wages in each period. Therefore, Model II is estimated after imposing the following parameter restrictions: $\{d_z = d_y = d_w = 0\}$. This model can be interpreted as a two-stage RBC model. The estimated parameter values of Model I and Model II are presented in Table 1.

The point estimate of d_w in Model I is 0.9250, implying that nominal wages are revised once every 13.3 quarters on average. The point estimate of d_y is 0.7325, meaning that the price of finished goods is readjusted once every 3.74 quarters on average. The other significant change in parameter values concerns ρ_π, which is much higher in Model I than in the benchmark model (2.13 *vs* 1.47). The business-cycle statistics implied by Model I are reported in Table 4. Hours worked are too volatile relative to output, whereas the relative volatility of investment and output is much too low. Real wages are strongly countercyclical, and the correlation between hours and productivity is strongly negative. Also, based on the likelihood ratio test (bottom of Table 1), the benchmark model is strongly preferred by the data to Model I.

Model II does not perform well either, being prone to the problems usually encountered in standard (one-stage) RBC models. The relative volatility of hours and output is much too low. The relative volatility of real wages to output is too high. Real wages and productivity are both strongly procyclical. The correlation between hours and productivity is strongly positive. Based on the likelihood ratio test, the benchmark model is strongly preferred by the data to Model II.

5 Conclusion

Real business cycle theory claims that technology shocks account for the bulk of short-run output fluctuations. However, a recent strand of literature has questioned their importance for business cycles (e.g., Galí, 1999; Christiano, Eichenbaum and Vigfusson, 2004; Basu, Fernald and Kimball, 2006). We have proposed in this paper a framework in which production chains play a key role in the transmission of technological change. We have found that technology shocks cannot easily be dismissed as a main source of the postwar business cycle. Our evidence also shows that nominal rigidities make our framework successful in capturing the salient features of postwar business cycles.

Unlike one-stage models with nominal rigidities (e.g., Galí, 1999), our two-stage framework delivers rich predictions concerning the dynamics of employment during the business cycle. Our evidence suggests that a technology improvement may either have a contractionary or expansionary effect on employment depending on the source of technological change. The model identifies the input-output linkage between firms operating at different stages of production and movements in relative prices triggered by exogenous variations in the pace of technology as key factors determining the response of hours worked to a technology shock. Despite the dominance of technology shocks, the two-stage framework delivers a near-zero correlation between hours and productivity and mildly procyclical real wages, two facts which have been hard to reconcile with technology-driven business cycle models.

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Table 1: Parameter Estimation Results

	Benchmak Model		Model I		Model II	
Parameter	Estimate	Std Error	Estimate	Std Error	Estimate	Std Error
$\rho_{A,y}$	0.8716	0.0177	0.8573	0.0090	0.8524	0.0145
$\rho_{A,z}$	0.9600	0.0711	$---$	$---$	0.9600	0.0014
ρ_v	0.1571	0.0335	0.6232	0.0366	0.3177	0.0302
ρ_κ	0.9512	0.0171	0.9108	0.0137	0.7188	0.0445
$\sigma_{A,y}$	0.0181	0.0007	0.0187	0.0010	0.0123	0.0008
$\sigma_{A,z}$	0.0197	0.0060	$---$	$---$	0.0086	0.0003
σ_v	0.0232	0.0020	0.0059	0.0003	0.0079	0.0002
σ_κ	0.0133	0.0006	0.0101	0.0010	0.0052	0.0002
ρ_R	0.0918	0.0767	0.0000	$---$	0.0363	0.0597
ρ_π	1.4702	0.0793	2.1285	0.0574	0.9984	0.0013
ρ_y	-0.0050	0.0060	-0.0122	0.0039	-0.0153	0.0020
d_w	0.8461	0.0079	0.9250	0.0313	$---$	$---$
d_y	0.6561	0.0256	0.7325	0.0063	$---$	$---$
d_z	0.6992	0.0539	$---$	$---$	$---$	$---$
φ_k	9.5827	0.6927	11.1243	0.2791	7.4139	0.5207
φ_y	5.7406	1.8588	2.4015	0.2979	5.9127	0.8304
φ_z	3.3746	1.1554	$---$	$---$	1.7069	0.5428
ϕ	0.2416	0.1312	$---$	$---$	0.4954	0.0245
b	0.0744	0.0389	0.2521	0.0595	0.1792	0.0198
γ	0.0701	0.1537	0.2974	0.0450	0.1131	0.0215
α_y	0.1300	0.0128	0.2564	0.0229	0.1333	0.0520
α_z	0.3407	0.0461	$---$	$---$	0.6110	0.0298
η	0.8831	0.4621	0.7120	0.3003	1.3040	0.0659
	$\mathcal{L} = 3567.40$		$\mathcal{L}_I = 3506.73$		$\mathcal{L}_{II} = 3387.33$	

Benchmark Model: Two-stage model with nominal rigidities; Model I: One-stage model with nominal rigidities; Model II: Two-stage model with flexible wages and prices

$\mathcal{L}$ denotes the maximized value of the log likelihood function. Then, the likelihood ratio statistic for the null hypothesis that the benchmark model is preferred to model I is equal to $2(\mathcal{L} - \mathcal{L}_I)$ that has a $\chi^2(4)$ distribution which gives a $p - value = 0.9999$.

Table 2: Benchmark Model: Variance Decomposition (Infinite Horizon)

Variable	$\varepsilon_{y,t}$	$\varepsilon_{z,t}$	$\varepsilon_{v,t}$	$\varepsilon_{\kappa,t}$
Y_t	5.12	72.38	14.76	7.74
Z_t	3.86	84.22	11.46	0.46
C_t	4.83	67.03	14.54	13.60
I_t	5.46	80.69	13.35	0.50
N_t	19.64	44.91	21.87	13.57
$N_{y,t}$	19.48	37.36	22.94	20.23
$N_{z,t}$	10.39	76.19	11.54	1.88
w_t	12.93	70.06	14.41	2.60
$\frac{Y_t}{N_t}$	47.89	48.48	1.98	1.64
$\pi_{y,t}$	14.67	10.25	71.58	3.50
$\pi_{z,t}$	0.70	7.80	89.51	1.99

Table 3: Benchmark Model: Variance Decomposition (Different Horizons)

Final-goods sector output (Y_t)

Quarters ahead	$\varepsilon_{y,t}$	$\varepsilon_{z,t}$	$\varepsilon_{v,t}$	$\varepsilon_{\kappa,t}$
1	15.64	30.95	50.63	2.78
4	6.52	52.07	35.81	5.60
8	5.80	62.26	24.71	7.22
12	6.29	65.69	20.20	7.82
20	6.00	68.48	17.38	8.13
40	5.36	71.21	15.45	7.98

Intermediary-goods sector output (Z_t)

Quarters ahead	$\varepsilon_{y,t}$	$\varepsilon_{z,t}$	$\varepsilon_{v,t}$	$\varepsilon_{\kappa,t}$
1	0.41	20.41	78.43	0.75
4	3.61	46.07	49.18	1.14
8	6.21	61.42	31.27	1.09
12	6.57	68.64	23.86	0.93
20	5.66	75.98	17.64	0.71
40	4.35	82.13	12.99	0.53

Final-goods sector inflation ($\pi_{y,t}$)

Quarters ahead	$\varepsilon_{y,t}$	$\varepsilon_{z,t}$	$\varepsilon_{v,t}$	$\varepsilon_{\kappa,t}$
1	12.09	6.73	77.98	3.19
4	14.99	6.49	74.84	3.67
8	14.39	8.10	73.97	3.52
12	14.51	9.45	72.59	3.44
20	14.73	9.92	71.89	3.44
40	14.69	10.08	71.70	3.50

Intermediary-goods sector inflation ($\pi_{z,t}$)

Quarters ahead	$\varepsilon_{y,t}$	$\varepsilon_{z,t}$	$\varepsilon_{v,t}$	$\varepsilon_{\kappa,t}$
1	0.11	2.25	95.71	1.94
4	0.62	4.49	92.83	2.06
8	0.67	6.67	90.65	2.01
12	0.67	7.43	89.90	1.99
20	0.68	7.54	89.79	1.99
40	0.70	7.68	89.63	1.99

Table 4: Second-Order Unconditional Moments in the Benchmark and Alternative Models

Moments	US data	Benchmark Model	Model I	Model II
$\frac{std(C)}{std(Y)}$	0.5062 (0.0204)	0.8334	0.9104	0.7642
$\frac{std(I)}{std(Y)}$	2.8681 (0.0836)	2.6380	2.2057	2.1711
$\frac{std(N)}{std(Y)}$	0.8543 (0.0611)	0.9277	1.3100	0.2184
$\frac{std(w)}{std(Y)}$	0.6372 (0.0712)	0.7965	0.8293	1.0218
$\frac{std(Y/N)}{std(Y)}$	0.5152 (0.0815)	0.4965	0.6780	0.8115
$\frac{std(N)}{std(Y/N)}$	1.7615 (0.0405)	1.8685	1.9320	0.2691
$\frac{std(\pi_y)}{std(\pi_z)}$	0.4753 (0.0646)	0.5540	$---$	0.9687
$Corr(Y,C)$	0.9105 (0.2345)	0.9909	0.9875	0.9615
$Corr(Y,I)$	0.9630 (0.2645)	0.9341	0.8378	0.9287
$Corr(Y,N)$	0.8192 (0.1860)	0.8700	0.8612	0.8909
$Corr(Y,Y/N)$	0.5188 (0.1856)	0.3886	−0.1891	0.9925
$Corr(N,Y/N)$	−0.0535 (0.1033)	−0.1163	−0.6619	0.8287
$Corr(Y,w)$	0.3721 (0.1804)	0.2472	−0.6873	0.9710
$Corr(Y/N,w)$	0.6727 (0.1705)	0.8506	0.7519	0.9629
$Corr(N,w)$	−0.0115 (0.1572)	−0.1888	−0.9138	0.8683
$Corr(\pi_y,\pi_z)$	0.7503 (0.2694)	0.8055	$---$	0.8848

Table 5: Second-Order Conditional Moments in the Benchmark Model

Moments	US data	Benchmark Model				
		All shocks	ε_y	ε_z	Supply shocks	Demand shocks
$\frac{std(C)}{std(Y)}$	0.5062 (0.0204)	0.8334	0.8090	0.8020	0.8025	0.9320
$\frac{std(I)}{std(Y)}$	2.8681 (0.0836)	2.6380	2.7228	2.7854	2.7813	2.0698
$\frac{std(N)}{std(Y)}$	0.8543 (0.0611)	0.9277	1.8165	0.7308	0.8467	1.1644
$\frac{std(w)}{std(Y)}$	0.6372 (0.0712)	0.7965	1.2652	0.7836	0.8242	0.6927
$\frac{std(Y/N)}{std(Y)}$	0.5152 (0.0815)	0.4965	1.5179	0.4064	0.5536	0.1993
$\frac{std(N)}{std(Y/N)}$	1.7615 (0.0405)	1.8685	1.1967	1.7982	1.5295	5.8411
$\frac{std(\pi_y)}{std(\pi_z)}$	0.4753 (0.0646)	0.5540	2.5391	0.6351	0.9486	0.5019
$Corr(Y, C)$	0.9105 (0.2345)	0.9909	0.9951	0.9948	0.9948	0.9877
$Corr(Y, I)$	0.9630 (0.2645)	0.9341	0.9691	0.9691	0.9691	0.8057
$Corr(Y, N)$	0.8192 (0.1860)	0.8700	0.5493	0.9366	0.8329	0.9946
$Corr(Y, Y/N)$	0.5188 (0.1856)	0.3886	0.0015	0.7765	0.5325	−0.7931
$Corr(N, Y/N)$	−0.0535 (0.1033)	−0.1163	−0.8348	0.5065	−0.0250	−0.8523
$Corr(Y, w)$	0.3721 (0.1804)	0.2472	−0.2865	0.6248	0.5257	−0.8916
$Corr(Y/N, w)$	0.6727 (0.1705)	0.8506	0.9208	0.9528	0.8771	0.8428
$Corr(N, w)$	−0.0115 (0.1572)	−0.1888	−0.9272	0.3252	0.0473	−0.9099
$Corr(\pi_y, \pi_z)$	0.7503 (0.2694)	0.8055	0.4612	−0.0250	0.0861	0.9568

Figure 1: Impulse Responses to an Intermediate-Stage Technology Shock

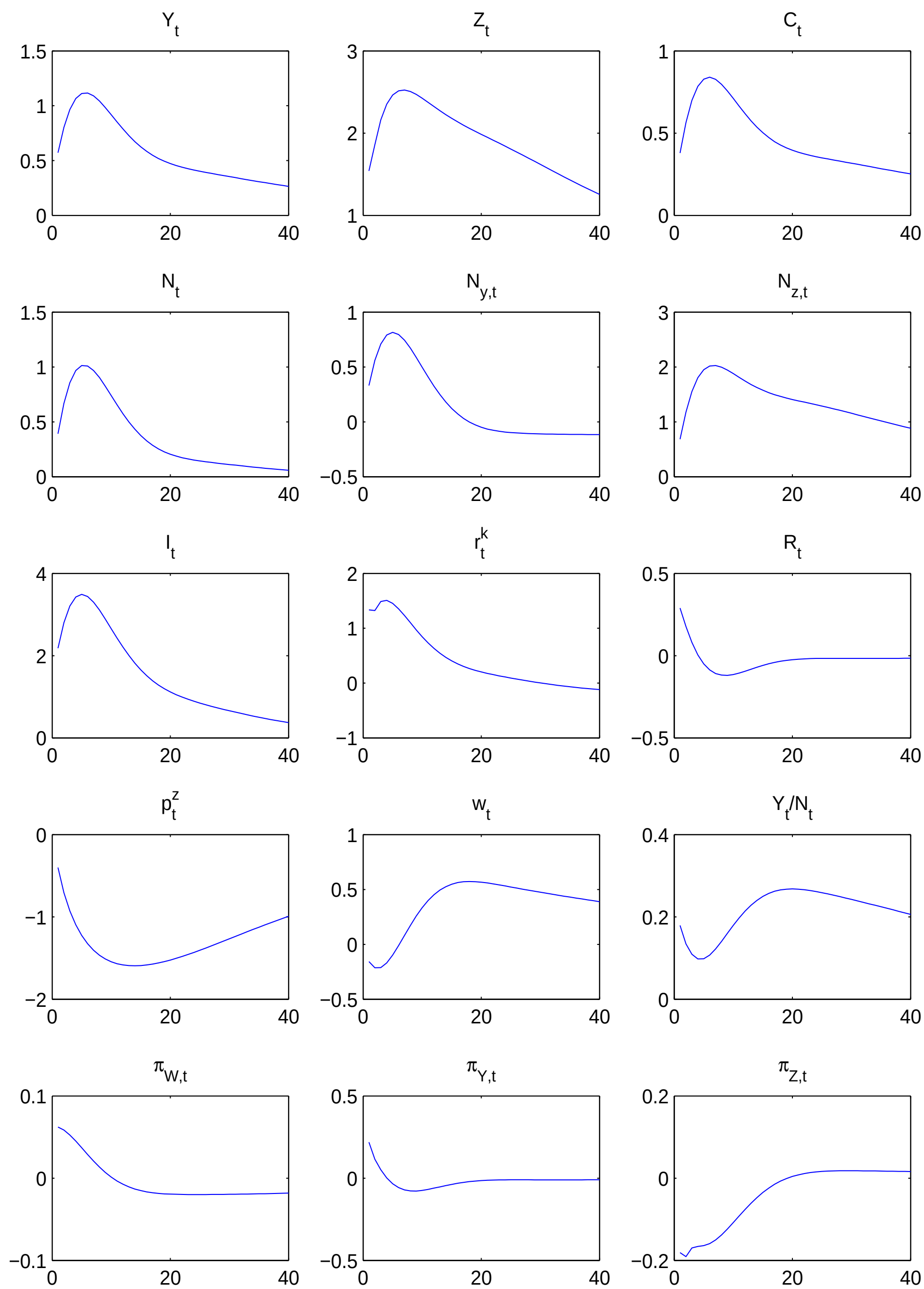


Figure 2: Impulse Responses to a Final-Stage Technology Shock

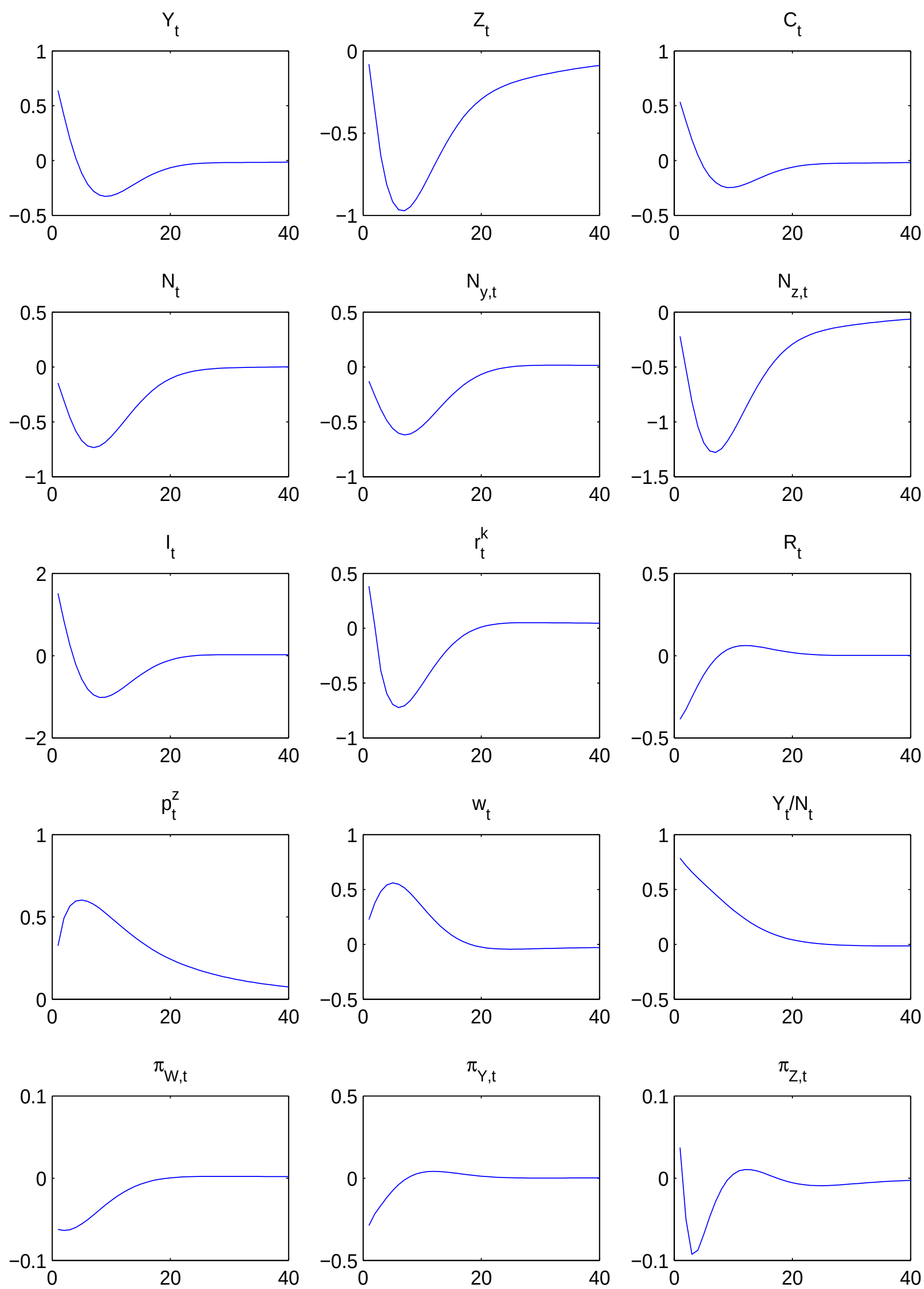
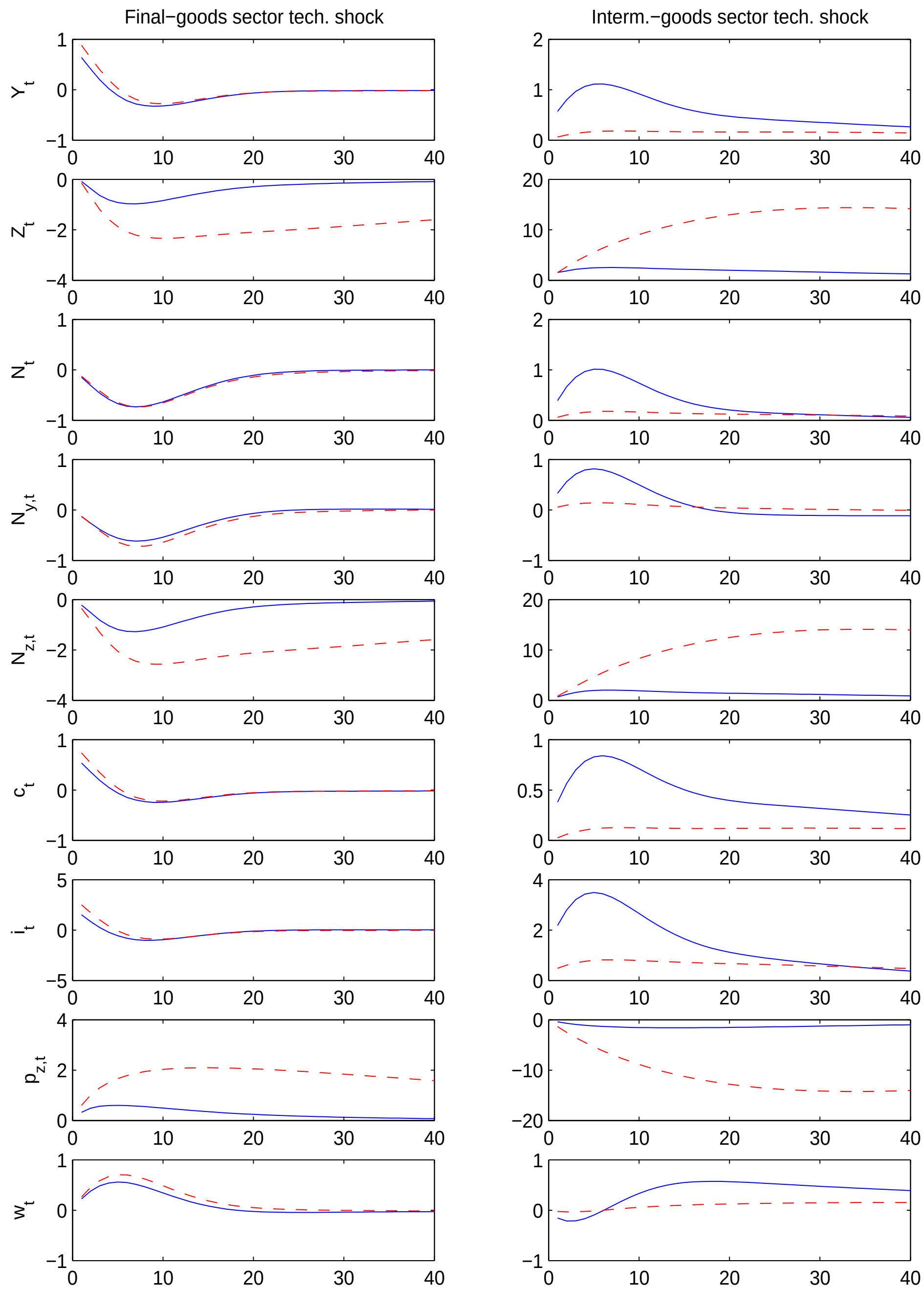
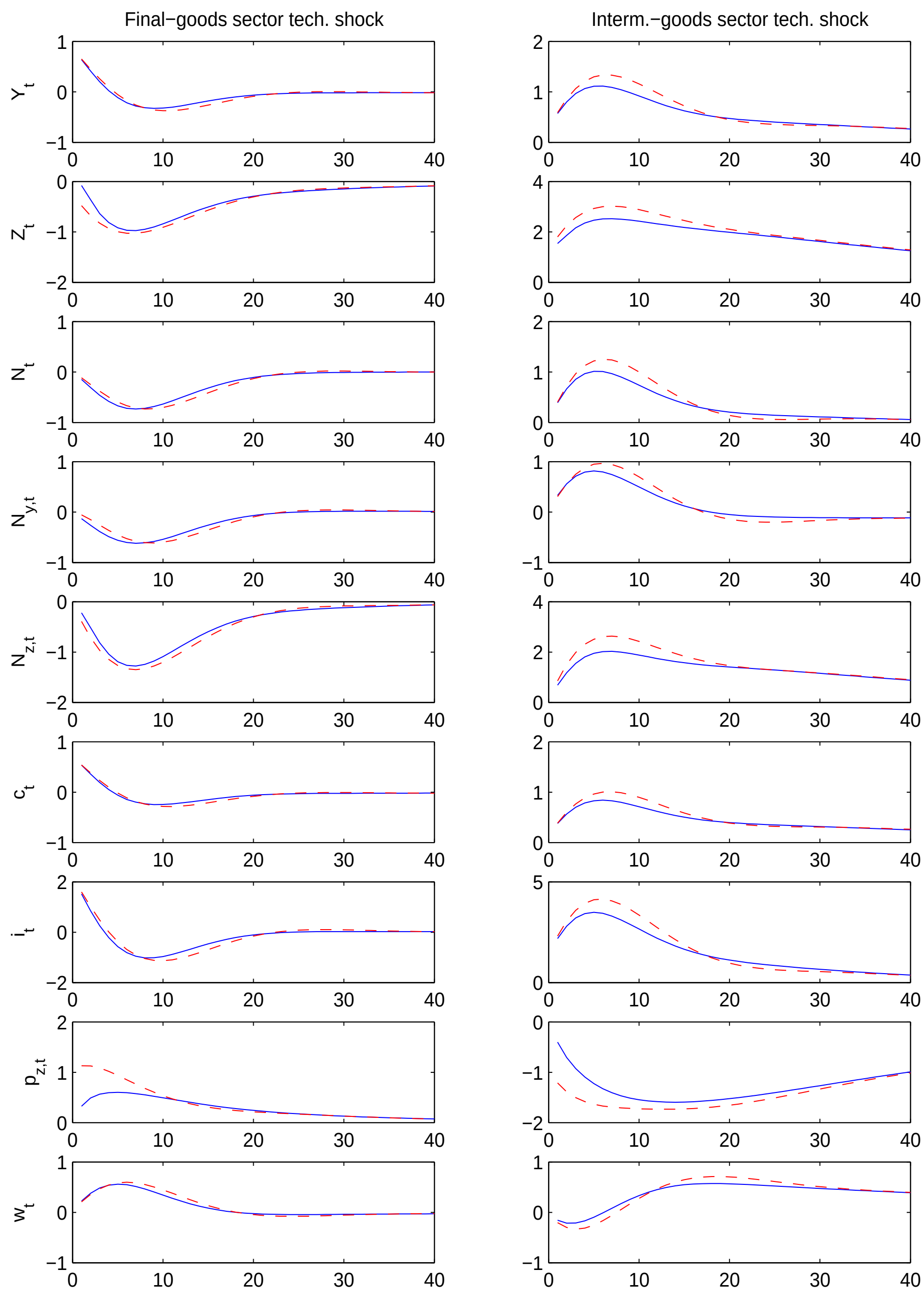


Figure 3: The Role of the Share of Intermediate Goods, ϕ



solid line: $\phi = 0.2416$; dashed line: $\phi = 0.0100$

Figure 4: The Role of Nominal Price Rigidities, d_y and d_z



solid line: $d_y = 0.6561$ and $d_z = 0.6992$; dashed line: $d_y = d_z = 0.0000$

Figure 5: The Role of the Persistence of Final-Stage Technology Shocks, $\rho_{A,y}$