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Sticky Wages and Sectoral Labor Comovement

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Abstract

A defining feature of business cycles is the comovement of inputs at the sectoral level with aggregate activity. Standard models cannot account for this phenomenon. This paper develops and estimates a two-sector dynamic general equilibrium model that can account for this key regularity. My model incorporates three shocks to the economy: monetary policy shocks, neutral technology shocks, and embodied technology shocks in the capital-producing sector. The estimated model is able to account for the response of the U.S. economy to all three shocks. Using this model, I argue that the key friction underlying sectoral comovement is rigidity in nominal wages.

Key words: comovement; business cycles; sticky wages

JEL classification: E20, E32, O41, O42

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1 Introduction

Comovement refers to the fact that, empirically, the level of economic activity across different sectors of the economy tends to move in the same direction along the business cycle: When the economy is in a boom, the majority of sectors use more inputs (capital and labor) and produce more output.

This paper develops and estimates a two-sector dynamic general equilibrium model that can account for this key regularity. My model incorporates three shocks to the economy: neutral technology shocks in the consumption and investment goods sectors, embodied technology shocks in the capital-producing sector, and monetary policy shocks.

Nominal wage stickiness is the feature of the model that is crucial for obtaining comovement in response to technology shocks of either kind. Both consumption and investment increase in response to positive technology shocks. Households' desire to smooth consumption translates into a relative shift of demand from consumption to investment goods. Labor demand increases, but wage rigidities prevent the wage from fully adjusting. Firms in the consumption goods sector face an increase in demand and a (relatively small) increase in the wage rate. The first effect dominates and firms hire more workers.

Standard models cannot account for comovement in response to technology shocks. Both neutral and embodied technology shocks produce a countercyclical labor input for the consumption goods sector.

In standard real business cycle (RBC) models,[1] the nominal wage fully adjusts to the increase in labor demand. The effect of the higher wage offsets the increase in demand for consumption goods, and firms in the consumption goods sector hire fewer workers. Economy-wide competitive factor markets imply that the capital-to-labor ratio is equated across sectors. Hence, capital is also reallocated to the investment goods sector in response to a positive technology shock. In other words, standard RBC models predict that inputs in the consumption goods sector comove *negatively* with inputs in the investment goods sector and with aggregate output.[2]

Monetary policy is the third source of fluctuations in the model. Monetary policy shocks generate an increase in economic activity in both sectors and would produce comovement even if wages were flexible. However, nomi-

[1] For an exposition of the standard RBC model see Hansen (1985) and Prescott (1986).

[2] Despite using fewer resources, the consumption goods sector produces more output because of the increased productivity.

nal wage rigidities play an important role in generating a persistent response of economic activity to monetary policy shocks.

A quantitative assessment of the role of sticky wages in generating comovement requires a rich model. My model incorporates frictions that are standard in the literature studying the effects of monetary policy.[3] The real side of the model incorporates investment adjustment costs, variable capital utilization, and habit formation preferences in consumption. Moreover, firms must borrow working capital to finance the wage bill. The model incorporates nominal price rigidities, in the form of sticky prices à la Calvo (1983).

The estimated model generates comovement of sectoral labor inputs in accordance with the data. Furthermore, my model is able to account for the response of the U.S. economy to all three shocks. The parameter estimates imply a plausible wage rigidity (3.7 quarters) and a modest degree of price stickiness. Estimates of the other parameters of the model, when comparable, and the model responses to neutral technology and monetary policy shocks are consistent with results in the literature.

Sticky wages deliver plausible empirical implications for my model by creating a countercyclical wedge between the real wage and the marginal rate of substitution between consumption and leisure. The existence of a "wage markup" over the marginal rate of substitution between consumption and leisure has been extensively documented empirically (see Galí, Gertler, and López-Salido, 2007).[4] My model generates a wage markup whose cyclical component has properties similar to its empirical counterpart.

The following section presents comovement in the U.S. data, the counterfactual implications of standard business cycle models, and shows how sticky wages generate comovement. Section 3 describes the model economy in detail. Section 4 is devoted to the model estimation and to the analysis of the comovement properties of the estimated model. Section 5 concludes. An appendix provides details on the data used.

[3] See, for example, Christiano et al. (2005), Altig et al. (2002), Smets and Wouters (2003), and Smets and Wouters (2005). The last three papers also examine the effect of other shocks to the economy.

[4] See also Hall (1997) and Chari et al. (2007).

2 The Comovement Puzzle

Comovement is a defining feature of business fluctuations. According to Burns and Mitchell (1946, p. 3),

> a cycle consists of expansions occurring at about the same time in many economic activities, followed by similarly general recessions, contractions, and revivals which merge into the expansion phase of the next cycle,

a definition endorsed by Gordon (1986).[5] Lucas (1977), Long and Plosser (1983), and Christiano and Fitzgerald (1998) define business cycles in a similar way.[6]

In this section I document comovement of sectoral inputs and outputs with aggregate output at business cycle frequencies for U.S. data. I then illustrate why the standard RBC model implies negative comovement and how the inclusion of sticky wages solves the comovement puzzle.

2.1 Comovement in the U.S. Data[7]

Figure 1 displays the cyclical components[8] of output, consumption, investment, and the corresponding labor inputs for the U.S. over the period 1964:Q1-2001:Q4.

Sectoral outputs (consumption and investment) and labor inputs comove with aggregate output. Table 1 reports correlations of sectoral outputs and labor inputs with aggregate output at business cycle frequencies (third column). The second column displays the standard deviations of sectoral outputs/inputs relative to the standard deviation of aggregate output. Consumption is half as volatile as output. Investment is 3.7 times more volatile

[5] The NBER Business Cycle Dating Committee (Hall et al., 2003), defines a recession as follows: "A recession is a significant decline in activity spread across the economy, lasting more than a few months, visible in industrial production, employment, real income, and wholesale-retail sales."

[6] Other authors, such as Schumpeter (1939, p. 200), Prescott (1986, p. 10) and Sargent (1987, p. 282), focus on the comovement of economy-wide variables in defining business fluctuations.

[7] See Christiano and Fitzgerald (1998) for a more disaggregated analysis of the comovement properties of the U.S. economy.

[8] The business cycle component is extracted using an HP_{1600} filter applied to the series in logs. See Appendix A for a description of the data used.

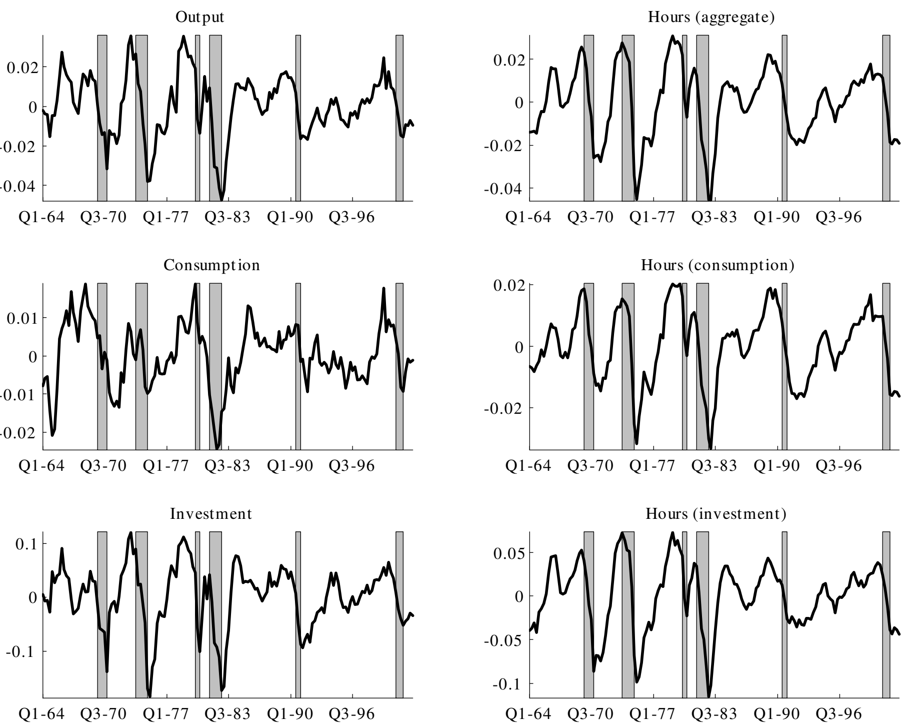

Figure 1: Cyclical components of aggregate output, sectoral outputs, and corresponding labor inputs.

than output. Both consumption and investment are highly correlated with output. The second moments of the corresponding labor inputs display similar properties.

Variable (x)	$\sigma_x/\sigma_{\tilde{y}}$	$\rho_{x,\tilde{y}}$
Consumption	0.53	0.70
Hours (consumption sector)	0.74	0.85
Investment	3.69	0.92
Hours (investment sector)	2.44	0.88

Table 1: Second moments of the cyclical components of consumption, investment, and corresponding labor inputs

The series were logged and detrended using an HP_{1600} filter. $\sigma_x/\sigma_{\tilde{y}}$ is the std. dev. of variable x relative to output, $\tilde{y}$. $\rho_{x,\tilde{y}}$ is the correlation of variable x with output, $\tilde{y}$.

2.2 The Puzzle

The standard RBC model can be interpreted as a two-sector model where consumption and investment goods are produced using the same technology:

$$\begin{aligned} C_t &= e^{z_t} \left(k_{C,t}\right)^{\alpha} \left(l_{C,t}\right)^{1-\alpha}, \\ I_t &= e^{z_t} \left(k_{I,t}\right)^{\alpha} \left(l_{I,t}\right)^{1-\alpha}, \end{aligned}$$

where k_x and l_x are capital and labor employed in sector $x = C, I$. Neutral technology shocks are denoted by z.

Firms in the consumption goods sector hire labor to the point where the marginal cost, the real wage, equals the marginal product of labor:

$$w_t = (1-\alpha)\frac{C_t}{l_{C,t}}. \tag{1}$$

For ease of exposition, assume that preferences over consumption and leisure are summarized by the utility function $u(c,l) = (\log c - \psi \log l)$. Households' labor supply is determined by equating the marginal rate of substitution between consumption and leisure to the real wage rate[9]:

$$w_t = \psi C_t l_t, \tag{2}$$

where ψ is a nonnegative constant.

Equations (1) and (2) imply that $l_{C,t} l_t$ is constant. Aggregate labor, l_t, increases in response to technology shocks. In order for $l_{C,t} l_t$ to remain constant, $l_{C,t}$ must decrease. Also, since the two sectors have identical capital-to-labor ratios,[10] capital will be moved from the consumption goods sector to the investment goods sector.[11]

Christiano and Fitzgerald (1998) show that the result is robust to the choice of functional form for the utility function within the class of preferences consistent with balanced growth (see King et al., 1988).[12]

Christiano and Fitzgerald (1998) also show that a non-unit elasticity of substitution between capital and labor in the production function could generate comovement. However, they argue that the standard model does not generate comovement for plausible values of the elasticity of substitution.

2.3 Sticky wages and comovement

In a model with sticky wages, households are not allowed to equate the marginal rate of substitution between consumption and leisure to the real wage. Let γ_t denote the wedge between the two:

$$\gamma_t = \frac{w_t}{\psi C_t l_t}. \tag{3}$$

Sticky wages create a time-varying markup of the price on the marginal cost of the good supplied. The real wage can be interpreted as the price of leisure, and the marginal rate of substitution between consumption and leisure is the marginal cost, measured in consumption units. In response to

[9] I am assuming that preferences over consumption and leisure are summarized by the utility function $u(c, l) = (\log c - \psi \log l)$ for ease of exposition.

[10] This follows from the fact that there are economy-wide factor markets.

[11] For a review of the literature that addresses the comovement puzzle in RBC models, see Christiano and Fitzgerald (1998).

[12] Boldrin et al. (2001) argue that introducing habit persistence in consumption does not solve the puzzle. In their model, productive-factors immobility is also needed to solve the comovement puzzle.

a technology shock, the denominator increases but sticky wages prevent the numerator from increasing by the same amount, and γ_t decreases.

Combining the household's intratemporal equation with the first-order condition for labor for firms in the consumption goods sector, (1), and rearranging results in

$$\frac{1}{1-\alpha} l_{C,t} l_t = \frac{1}{\gamma_t}. \tag{4}$$

A countercyclical wage markup implies that $l_{C,t} l_t$ is procyclical. Thus $l_{C,t}$ can be procyclical as well, and the puzzle is solved.

To evaluate empirically the relevance of nominal wage rigidities in generating comovement, I present in the following section a two-sector DSGE model that incorporates sticky wages and several other departures from the basic RBC model. One-sector models featuring similar frictions have been recently used to study business cycles and/or the effects of monetary policy: see Christiano et al. (2005), Altig et al. (2002), Smets and Wouters (2003), and Smets and Wouters (2005). A growing literature presents multi-sector DSGE models to study different issues: international monetary policy coordination (Liu and Pappa, 2008), learning and productivity shifts (Edge et al., 2007), productivity analysis in open economies (Guerrieri et al., 2005), and firm-specific capital and the role of nominal rigidities over the cycle (Altig et al., 2005), to cite a few. A formal comparison with other multi-sector models is beyond the scope of this paper. However, the main point —i.e., the connection between sectoral inputs comovement and nominal wage rigidities— is quite general, as discussed above.

3 The Model

The economy is populated by a unit measure continuum of households. Each household makes consumption, investment, capital utilization, cash holding, and deposit decisions. Also, each household supplies monopolistically a differentiated labor service to a competitive labor market intermediary. The homogenous composite labor is supplied to monopolist intermediate goods firms in the consumption and investment goods sectors. An intermediate firm in either sector combines labor services and capital services into an intermediate input for the production of the final good in the respective sector. Intermediate good producers need to borrow money from a competitive financial intermediary to pay for the wage bill before production takes place. Final good producers are perfectly competitive. Finally, the monetary authority implements monetary policy by setting the money growth rate.

In every period the economy is affected by three different shocks. A neutral (disembodied) technology shock increases the productivity of intermediate good producers in either sector. An investment-specific (embodied) technology shock increases the productivity of only intermediate goods producers in the investment goods sector. Monetary policy shocks affect the growth rate of the money supply, beyond the endogenous response of monetary policy to realizations of the other shocks.

3.1 Timing

At the beginning of every period, embodied and disembodied technology shocks are realized. Then, prices and wages are set and households make their consumption, investment, and capital utilization decisions. After this, the monetary policy shock is realized. Then, households make their portfolio decision; goods and labor markets meet and clear; production, investment, and consumption occur. To reflect the fact that different decisions are based on different information, let Ω_t be the information set including all the shock realizations up to and including time t and Ω_t^m be the information set including all the shock realizations up to t, excluding the time t realization of the monetary policy shock. The corresponding conditional expectations operators are denoted by

$$E\left(\bullet|\Omega_t\right) = E_t\left(\bullet\right),\ E\left(\bullet|\Omega_t^m\right) = E_t^m\left(\bullet\right).$$

The timing described above ensures that the identification assumptions used to identify monetary policy shocks in the data hold by construction in the model.

3.2 Final goods firms

In either sector, final goods output is produced by competitive firms according to the technology

$$Y_{x,t} = \left[\int_0^1 \left(Y_{x,j,t}\right)^{\frac{1}{\lambda_f}}\right]^{\lambda_f},\ \lambda_f \in [1, +\infty),\ x = C, I, \tag{5}$$

where $Y_{x,j,t}$ denotes the time t input of intermediate good j for sector x.

Consumption and investment goods producers solve

$$\max_{Y_{x,t},\{Y_{x,j,t}\}_{j\in[0,1]}} P_{x,t}Y_{x,t} - \int_0^1 P_{x,j,t}Y_{x,j,t}dj,\ x = C, I, \tag{6}$$

where $P_{x,t}$ is the price of final good x.

3.3 Intermediate Goods Firms

Intermediate good $j \in [0,1]$ for the consumption goods sector is produced according to

$$Y_{C,j,t} = \max\left\{e^{z_{N,t}}\left[(K_{C,j,t})^{\alpha}(l_{C,j,t})^{1-\alpha} - \phi_C (Z_{t-1})^{\alpha}\right], 0\right\}, \tag{7}$$

where $\alpha \in (0,1)$, $\phi_C > 0$, $K_{C,j,t}$ and $l_{C,j,t}$ denote capital and labor services, and $z_{N,t}$ represents a neutral technology shock. The term $e^{z_{N,t}}\phi_C (Z_{t-1})^{\alpha}$ is a "fixed" production cost that ensures that profits are zero in a non-stochastic steady state.[13]

Intermediate investment goods $j \in [0,1]$ is produced according to:

$$Y_{I,j,t} = \max\left\{e^{z_{N,t}+z_{I,t}}\left[(K_{I,j,t})^{\alpha}(l_{I,j,t})^{1-\alpha} - \phi_I (Z_{t-1})^{\alpha}\right], 0\right\}, \tag{8}$$

where $K_{I,j,t}$ and $l_{I,j,t}$ denote capital and labor services, and $z_{I,t}$ represents a capital-embodied shock. The term $e^{z_{N,t}+z_{I,t}}\phi_I (Z_{t-1})^{\alpha}$ is a "fixed" production cost that will ensure that profits are zero along a non-stochastic balanced growth path.

Technology shocks evolve as follows:

$$\begin{aligned} z_{x,t} &= z_{x,t-1} + \mu_{x,t}, \\ \mu_{x,t} &= (1-\rho_x)\mu_x + \rho_x \mu_{x,t-1} + \varepsilon_{x,t}, \\ |\rho_x| < 1,&\ \varepsilon_{x,t} \underset{iid}{\sim} N\left(0, \sigma_x^2\right),\ x = N, I. \end{aligned} \tag{9}$$

Let R_t^k and W_t denote the nominal rental rate on capital services and the wage rate. Firms need to borrow money to pay their wage bill in advance of production. Thus labor has a unit cost of $R_t W_t$.

[13] The "fixed" cost is assumed to grow at the same rate as sectoral output, to ensure that it does not become negligible.

The first-order conditions with respect to capital and labor imply that the capital-to-labor ratios across firms in each sector are identical and are equalized across sectors:

$$\frac{K_{x,j,t}}{l_{x,j,t}} = \frac{K_{x,t}}{l_{x,t}} = \frac{K_t}{l_t}, \forall j \in [0,1], \; x = C, I.$$

The typical intermediate goods firm's profits are

$$(P_{x,j,t} - P_{x,t} s_{x,t}) Y_{x,j,t}, \;\; x = C, I.$$

In each period, with constant probability $\left(1 - \xi_{p,x}\right)$, a firm in sector x is allowed to reoptimize its nominal price.[14] If a firm is not allowed to reoptimize, the following equations hold[15]:

$$\begin{aligned} P_{C,j,t} &= \pi_{C,t-1} P_{C,j,t-1}, \quad \pi_{C,t-1} \equiv \frac{P_{C,t-1}}{P_{C,t-2}}, \\ P_{I,j,t} &= e^{-\mu_{I,t}} \pi_{I,t-1} P_{I,j,t-1}, \quad \pi_{I,t-1} \equiv \frac{P_{I,t-1}}{P_{I,t-2}} e^{\mu_{I,t-1}}. \end{aligned}$$

Firms choose $\tilde{P}_{C,t}$ and $\tilde{P}_{I,t}$ in order to maximize[16]

$$\begin{aligned} &E_t^m \sum_{l=0}^{+\infty} \left(\beta \xi_{p,C}\right)^l \eta_{t+l} \left[\tilde{P}_{C,t} X_{C,t,l} - s_{C,t+l} P_{C,t+l}\right] Y_{j,t+l}^C, \\ &E_t^m \sum_{l=0}^{+\infty} \left(\beta \xi_{p,I}\right)^l \eta_{t+l} \left[\tilde{P}_{I,t} e^{-\left(z_{I,t+l} - z_{I,t}\right)} X_{I,t,l} - s_{I,t+l} P_{I,t+l}\right] Y_{j,t+l}^I, \end{aligned}$$

where

$$X_{x,t,l} = \begin{cases} \Pi_{j=0}^{l-1} \pi_{x,t+j} & \text{for } l \geq 1 \\ 1 & \text{for } l = 0 \end{cases}, \;\; x = C, I.$$

η_{t+l} is the marginal value of a dollar for the household, which firms take as given; $s_{x,t}$ denotes the marginal costs for firms in sector x.

[14] Independently across firms, within and between sectors, and time.

[15] See Christiano et al. (2005) for a justification of this updating rule, as opposed to the standard rule $P_{x,j,t} = \pi P_{x,j,t-1}$, where π is the unconditional average of inflation.

[16] All the firms in either sector that can reoptimize will choose the same price, as shown in Woodford (1996).

The aggregate prices in the two sectors can be expressed as:

$$P_{C,t} = \left[\left(1-\xi_{p,C}\right) \tilde{P}_{C,t}^{\frac{1}{1-\lambda_f}} + \xi_{p,C} \left(\pi_{C,t-1} P_{C,t-1}\right)^{\frac{1}{1-\lambda_f}} \right]^{1-\lambda_f}, \quad (10)$$

$$P_{I,t} = \left[\left(1-\xi_{p,I}\right) \tilde{P}_{I,t}^{\frac{1}{1-\lambda_f}} + \xi_{p,I} \left(\frac{\pi_{I,t-1} P_{I,t-1}}{e^{\mu_{I,t}}}\right)^{\frac{1}{1-\lambda_f}} \right]^{1-\lambda_f}. \quad (11)$$

3.4 Households

Households rank consumption, leisure, and real balances streams according to[17]

$$E_0 \sum_{t=0}^{+\infty} \beta^t \left[\log\left(C_t - bC_{t-1}\right) - \psi_l \frac{\left(h_{j,t}\right)^2}{2} + \psi_q \frac{\left(\frac{q_t}{\vartheta_t}\right)^{1-\sigma_q}}{1-\sigma_q} \right], \quad (12)$$

$$\beta \in (0,1), \; \sigma \in [0,+\infty), \; \psi_l \in (0,+\infty),$$
$$\psi_q \in (0,+\infty), \; \sigma_q \in [0,+\infty),$$

where $q_t \equiv Q_t/P_{C,t}$ are real money balances, $\vartheta_t = e^{\frac{\mu_{N,t}+\alpha\mu_{I,t}}{1-\alpha}}$ is a scaling variable, and $h_{j,t}$ is household j's labor supply.

The household's budget constraint is

$$\begin{aligned} M_{t+1} \leq\ & R_t \left[M_t - Q_t + M_{t+1}\left(\mu_t - 1\right)\right] + Q_t + A_{j,t} + D_t \\ & - P_{I,t} I_t - P_{C,t} C_t - P_{C,t} a\left(u_t\right) \frac{\vartheta_t}{Z_t} \bar{K}_t + R_t^k u_t \bar{K}_t + W_{j,t} h_{j,t}, \end{aligned} \quad (13)$$

where M_t is the household's beginning-of-period stock of money, $\left(\mu_t - 1\right) M_{t+1}$ is a lump sum transfer from the monetary authority, Q_t denotes the nominal cash balances the household carries from the previous period, D_t denotes profits, and $A_{j,t}$ is the net cash flow from state-contingent securities.[18] The amount $\left[M_t - Q_t + \left(\mu_t - 1\right) M_{t+1}\right]$ is deposited with a financial intermediary.

[17] The only functional form for utility consistent with identical consumption across households and with balanced growth is logarithmic in consumption.

[18] State-contingent securities allow the households to insulate consumption and asset holdings from the realizations of idiosyncratic Calvo uncertainty.

$\bar{K}_t$ denotes the physical stock of capital. The quantity of capital services is given by the product of physical capital and the utilization rate, u_t:

$$K_t = u_t \bar{K}_t. \tag{14}$$

The cost of utilizing capital is measured in consumption units and is proportional to the quantity of physical capital. In steady-state, utilization is normalized to one and it is costless, i.e. $a(1) = 0$.

The household's stock of capital evolves according to

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + F(I_t, I_{t-1}), \tag{15}$$

$$F(I_t, I_{t-1}) = \left[1 - S\left(\frac{I_t}{I_{t-1}}\right)\right] I_t,$$

$$S\left(e^{\frac{\mu_N+\mu_I}{1-\alpha}}\right) = S'\left(e^{\frac{\mu_N+\mu_I}{1-\alpha}}\right) = 0,\ \varkappa \equiv e^{2\frac{\mu_N+\mu_I}{1-\alpha}} S''\left(e^{\frac{\mu_N+\mu_I}{1-\alpha}}\right) > 0.$$

The function $S(\bullet)$ gives the adjustment cost to be paid if the investment growth rate is changed from its previous-period level.[19]

3.4.1 Labor Decision

The household labor supply decision is modeled as in Erceg et al. (2000). Households are monopoly suppliers of differentiated labor services, $h_{j,t}$. These services are sold to a representative, competitive firm, which aggregates them into homogeneous labor input according to

$$h_t = \left(\int_0^1 h_{j,t}^{\frac{1}{\lambda_w}} dj\right)^{\lambda_w},\ \lambda_w \in [1, +\infty).$$

The aggregate wage, W_t, is related to the individual households' wage rates as follows:

$$W_t = \left(\int_0^1 W_{j,t}^{\frac{1}{1-\lambda_w}} dj\right)^{1-\lambda_w}. \tag{16}$$

In each period a household is allowed to reoptimize its nominal wage, with constant probability $(1-\xi_w)$,[20] taking W_t and h_t as given. If the household

[19] See Christiano et al. (2005) for a detailed discussion of this specification of investment adjustment costs and a comparison with adjustment costs in the investment rate.

[20] Independently across households, sectors, and time.

is not allowed to reoptimize, its wage evolves according to[21]

$$W_{j,t+1} = \pi_{C,t} e^{\frac{\mu_N + \alpha\mu_I}{1-\alpha}} W_{j,t}.$$

The first-order condition associated with the wage choice,[22] $\tilde{W}_t$, of a household that is reoptimizing is

$$E_t^m \sum_{l=0}^{+\infty} (\beta\xi_w)^l \frac{h_{j,t+l}}{C_{t+l}} \left[\exp\left(\frac{\mu_N + \alpha\mu_I}{1-\alpha} l \right) \frac{\tilde{W}_t X_{C,t,l}}{P_{C,t+l}} - \lambda_w h_{j,t+l} C_{t+l} \right] = 0. \quad (17)$$

The aggregate wage can be expressed as

$$W_t = \left[(1-\xi_w) \left(\tilde{W}_t \right)^{\frac{1}{1-\lambda_w}} + \xi_w \left(e^{\frac{\mu_N + \alpha\mu_I}{1-\alpha}} \pi_{C,t-1} W_{t-1} \right)^{\frac{1}{1-\lambda_w}} \right]^{1-\lambda_w}. \quad (18)$$

3.5 Loan-market clearing

Loan-market clearing requires that the demand for loans from firms to finance their working capital is equal to money deposited by the households:

$$W_t l_t = \mu_t M_t - Q_t. \quad (19)$$

3.6 Sectoral resource constraints

The resource constraints for the consumption goods sector and the investment goods sector can be expressed as[23]

$$C_t + a(u_t) \frac{\vartheta_t}{Z_t} \bar{K}_t = e^{z_{N,t}} \left(\frac{P_{C,t}^*}{P_{C,t}} \right)^{\frac{\lambda_f}{\lambda_f - 1}} \left[\left(\frac{W_t^*}{W_t} \right)^{\frac{\lambda_w(1-\alpha)}{\lambda_w - 1}} K_{C,t}^{\alpha} h_{C,t}^{1-\alpha} - \phi_C Z_{t-1}^{\alpha} \right], \quad (20)$$

$$I_t = e^{z_{N,t} + z_{I,t}} \left(\frac{P_{I,t}^*}{P_{I,t}} \right)^{\frac{\lambda_f}{\lambda_f - 1}} \left[\left(\frac{W_t^*}{W_t} \right)^{\frac{\lambda_w(1-\alpha)}{\lambda_w - 1}} K_{I,t}^{\alpha} h_{I,t}^{1-\alpha} - \phi_I Z_{t-1}^{\alpha} \right], \quad (21)$$

[21] The results in section 4.3 are robust to the adoption of the partial indexation of wages to past inflation used in Smets and Wouters (2005).

[22] All the households that can reoptimize will choose the same wage.

[23] As shown in Yun (1996), the terms $\left(P_{x,t}^*/P_{x,t}\right)^{\frac{\lambda_f}{\lambda_f-1}}$ and $(W_t^*/W_t)^{\frac{\lambda_w(1-\alpha)}{\lambda_w-1}}$ do not have a first-order effect and they disappear in the log-linearized versions of the sectoral resource constraints.

where $K_{x,t}$ and $h_{x,t}$ measure capital and labor services used in sector x and

$$W_t^* = \left(\int_0^1 W_{j,t}^{\frac{\lambda_w}{1-\lambda_w}} dj \right)^{\frac{1-\lambda_w}{\lambda_w}}, \; P_{x,t}^* = \left(\int_0^1 P_{x,j,t}^{\frac{\lambda_f}{1-\lambda_f}} dj \right)^{\frac{1-\lambda_f}{\lambda_f}}, \; x = C, I.$$

3.7 Monetary Policy

Monetary policy is modeled as a money growth rule:

$$\begin{gathered} \hat{\mu}_t \equiv \hat{\mu}_{p,t} + \hat{\mu}_{N,t} + \hat{\mu}_{I,t}, \\ \hat{\mu}_{p,t} = \rho_{\mu_p} \hat{\mu}_{p,t-1} + \varepsilon_{\mu_p,t}, \; \varepsilon_{\mu_p,t} \underset{iid}{\sim} N\left(0, \sigma_{\mu_p}^2\right) \\ \hat{\mu}_{j,t} = \rho_{\mu_j} \hat{\mu}_{j,t-1} + c_{\mu_j} \varepsilon_{j,t} + l_{\mu_j} \varepsilon_{j,t-1}, \\ \left|\rho_{\mu_p}\right|, \left|\rho_{\mu_j}\right| < 1, \; j = N, I. \end{gathered} \tag{22}$$

Here, $\varepsilon_{\mu_p,t}$ represents a monetary policy shock. The terms $\hat{\mu}_{N,t}$ and $\hat{\mu}_{I,t}$ capture the response of monetary policy to innovations in neutral and capital-embodied technology, respectively. The dynamic response of $\hat{\mu}_{j,t}$ to $\varepsilon_{j,t}$ is characterized by ARMA(1,1) processes.

3.8 Equilibrium and Solution

A textbook sequence-of-markets notion of equilibrium applies.

The model described in the previous sections can be expressed in terms of stationary variables as follows:

$$\begin{gathered} c_t \equiv \frac{C_t}{\vartheta_t}, i_t \equiv \frac{I_t}{Z_t}, k_{C,t} \equiv \frac{K_{C,t}}{Z_{t-1}}, k_{I,t} \equiv \frac{K_{I,t}}{Z_{t-1}}, \\ w_t = \left(\frac{W_t}{P_{C,t}\vartheta_t} \right), \; r_t^k \equiv \left(\frac{R_t^k Z_t}{P_{C,t}\vartheta_t} \right), \\ p_{K_t'} \equiv \left(P_{K_t'} \frac{Z_t}{\vartheta_t} \right), \; p_{I,t} \equiv \frac{P_{I,t}}{P_{C,t}} \exp\left(z_{I,t}\right), \;\;, \\ \pi_{C,t} \equiv \frac{P_{C,t}}{P_{C,t-1}}, \; \pi_{I,t} \equiv \frac{P_{I,t}}{P_{I,t-1}} \\ m_t \equiv \frac{M_t}{P_{C,t}\vartheta_t}, q_t \equiv \frac{Q_t}{P_{C,t}\vartheta_t} \end{gathered}$$

where $Z_t = \exp\left(\frac{z_{N,t}+z_{I,t}}{1-\alpha}\right)$ and $\vartheta_t = \exp\left(\frac{z_{N,t}+\alpha z_{I,t}}{1-\alpha}\right)$. Aggregate and sectoral labor inputs, i.e., l, l_C, and l_I, are stationary.

I log-linearize the scaled model in a neighborhood of its non-stochastic steady-state and I solve the log-linearized model using the algorithm described in Anderson and Moore (1985) and the method of undetermined coefficients in Christiano (2002).[24]

4 Econometric Methodology

I estimate the key parameters of the log-linearized model with a standard limited information approach. The parameters are chosen in order to minimize the distance of the impulse responses of the model to embodied, disembodied, and monetary policy shocks from the impulse responses of a structural VAR representation of U.S. data.

4.1 A VAR Representation of the Data

The variables included in the VAR analysis are the growth rate of the real investment price, the growth rate of average labor productivity, the inflation rate, capacity utilization, the ratio of the real wage to average labor productivity, the consumption and investment shares of output, the federal funds rate, and the money growth rate. The sample covers the period 1959:Q2-2001:Q4. The variables are required to be covariance stationary. The estimated VAR coefficients corroborate the stationarity assumption.

Consider the following reduced-form VAR[25]:

$$\begin{aligned} Y_t &= A(L)\, Y_{t-1} + \upsilon_t, \;\; E(\upsilon_t \upsilon_t') = V, \\ A(L) &= A_1 + A_2 L + ... + A_p L^p, \;\; p < \infty \end{aligned}$$

In the analysis that follows Y_t is defined as

$$Y_t = \left[\begin{array}{c} \Delta \ln(p_{I,t}), \Delta \ln\left(\frac{Y_t}{l_t}\right), \pi_t, \ln\left(\frac{w_t}{Y_t/l_t}\right), \ln(u_t), \\ \ln(l_t), \ln\left(\frac{C_t}{Y_t}\right), \ln\left(\frac{I_t}{Y_t}\right), R_t, \Delta \ln(M_t) \end{array} \right]'.$$

The reduced-form residuals, υ_t, are related to the structural shocks, ϵ_t, by $\epsilon_t = A_0 \upsilon_t$. Also, the structural shocks are orthogonal to each other, i.e.,

[24] A technical appendix is available from the author upon request.

[25] In the estimation, four lags (i.e., $p = 3$) and a constant were included. For ease of exposition the constant has been omitted in what follows.

$E(\epsilon_t \epsilon_t') = I_{10}$. The first two elements of ϵ_t are the investment-specific and neutral technology shocks, respectively. The ninth element is the monetary policy shock. The remaining elements of ϵ_t are not identified.

Following Fisher (2006), I identify embodied and disembodied technology shocks using long-run restrictions. As in the model, investment-specific technology shocks are the only shocks to have a long-run effect on the relative price of investment. Neutral technology shocks and investment-specific technology shocks are the only shocks that affect average labor productivity in the long run. The long-run effects of the structural shocks are given by

$$Y_\infty = \Theta \epsilon_t,$$
$$\Theta \equiv [I - A(1)]^{-1} A_0^{-1}.$$

The identifying assumptions described above boil down to assuming that the first two rows of matrix Θ have the following structure:

$$\Theta(1:2,:) = \begin{bmatrix} \theta_{11} & 0 & 0_{1\times 8} \\ \theta_{21} & \theta_{22} & 0_{1\times 8} \end{bmatrix}.$$

Monetary policy shocks are identified as in Christiano et al. (1999) by assuming that the ninth column of A_0 has the following structure[26]:

$$A_0(:,9) = [0_{1\times 8}, a_0, a_1]'.$$

That is, the variables ordered before the interest rate in the VAR do not respond contemporaneously to monetary shocks.

Figures 2-4 report the impulse response functions (IRFs) of the VAR to the three structural shocks. The shaded areas are bootstrapped 95% confidence intervals around the point estimates. The responses to technology shocks are consistent with the evidence reported by Fisher (2003, 2006). Monetary policy shocks produce the patterns of responses that are well-documented in the literature. In particular, they generate persistent output and inflation responses and hump-shaped responses of consumption, investment, and hours.

Altig et al. (2005) estimate the same VAR specification and argue that embodied and disembodied technology shocks and monetary shocks account

[26]Notice that there are two overidentifying restrictions. The first two elements of ϵ_t would be just-identified by imposing the long-run restrictions. The identification of monetary policy shocks poses two additional zero restrictions.

for a substantial amount of the volatility of aggregate quantities at business cycle frequencies.

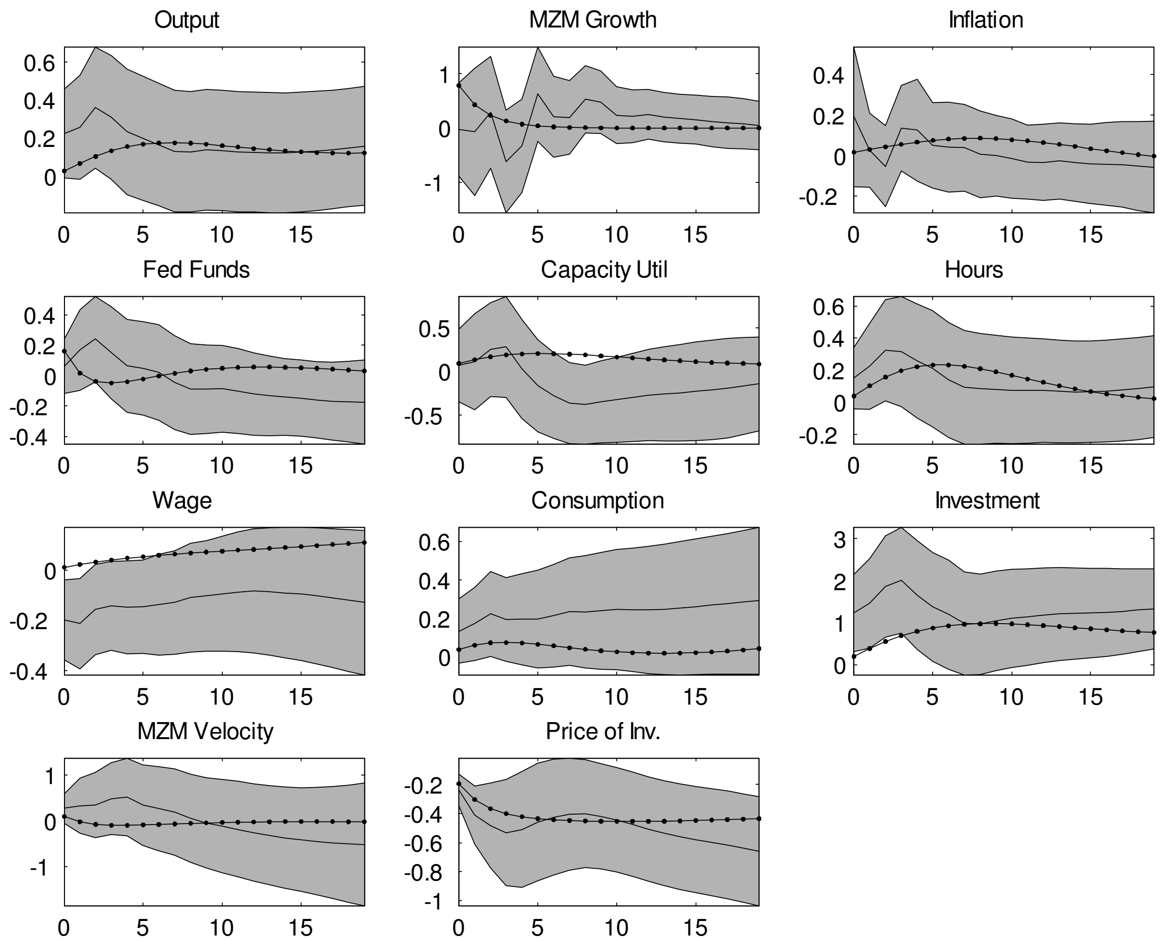

Figure 2: Model (lines with points) and VAR-based (solid lines) responses to an embodied technology shock.

4.2 Estimation

The model parameters are collected in the vector $\zeta = [\zeta_1,\ \zeta_2]'$. The elements of ζ_1 have been fixed at the same values as in Altig et al. (2002) (Table 2).

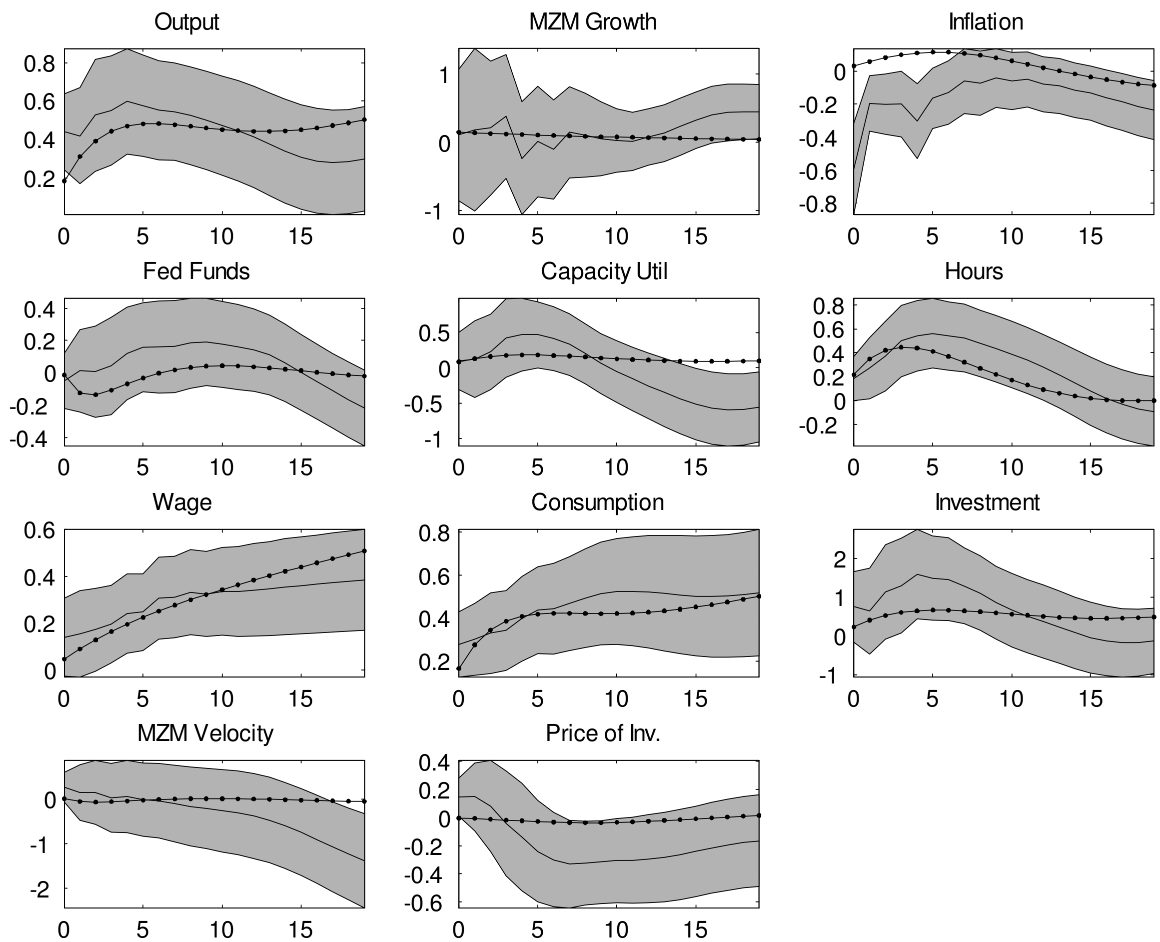

Figure 3: Model (lines with points) and VAR-based (solid lines) responses to a neutral technology shock.

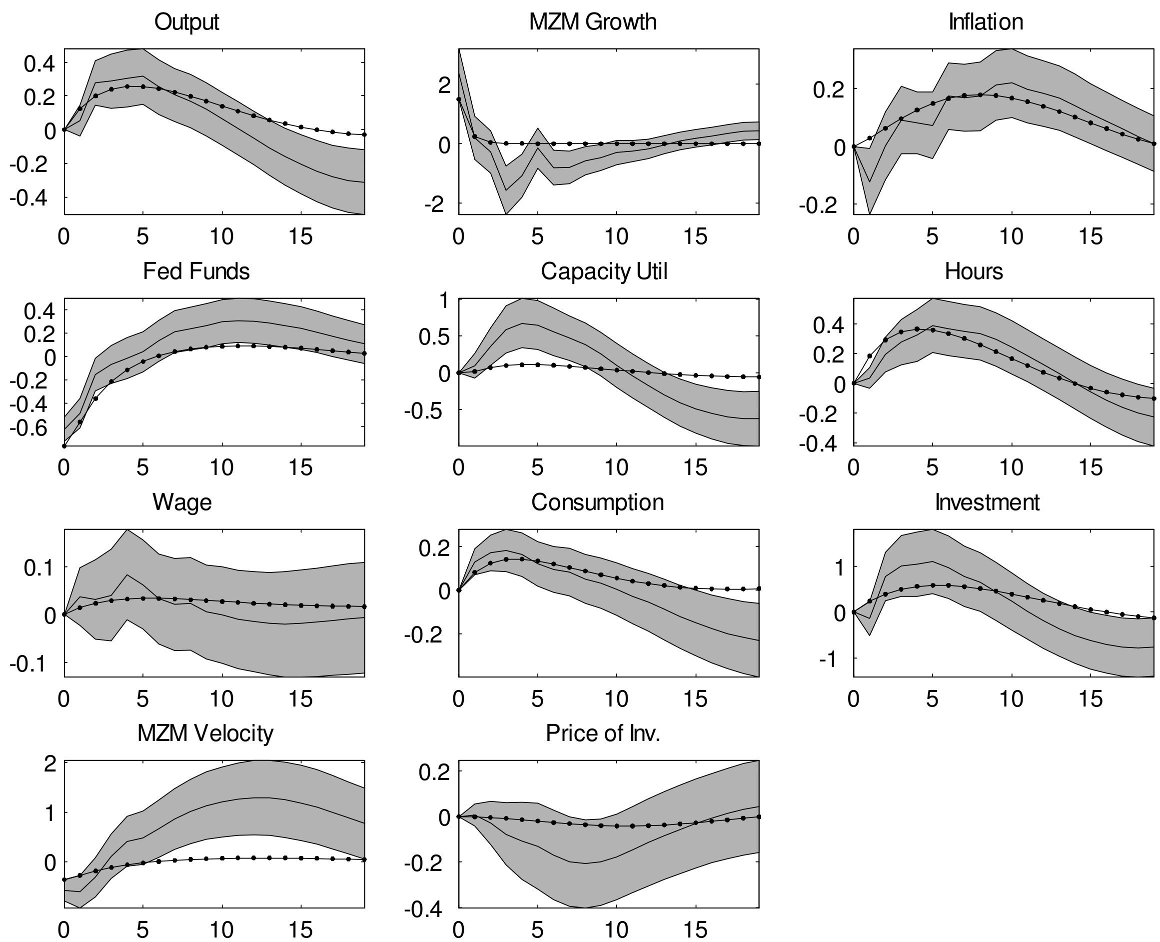

Figure 4: Model (lines with points) and VAR-based (solid lines) responses to a monetary policy shock.

Parameter in ζ_1	Value
β	$(1.03)^{-1/4}$
α	0.36
δ	0.025
μ	1.017
σ_l	1
ψ_l	s.t. $l = 1$
ψ_q	s.t. $q/m = 0.25$
λ_w	1.05
μ_N	0.002
μ_I	0.003

Table 2: Fixed parameters

σ_q	b	λ_f	$\xi_{p,C}$	$\xi_{p,I}$	ξ_w	κ	σ_a
10.46 (5.56)	0.76 (0.09)	1.21 (0.11)	0.54 (0.11)	0.77 (0.22)	0.73 (0.09)	3.54 (2.13)	0.08 (0.14)

Table 3: Estimated economic parameters - std. errors in parentheses

ρ_{μ_p}	ρ_{μ_N}	c_{μ_N}	l_{μ_N}	ρ_{μ_I}	c_{μ_I}	l_{μ_I}	ρ_N	ρ_I	σ_{μ_p}	σ_N	σ_I
0.13 (0.28)	0.30 (0.41)	6.96 (2.67)	2.70 (3.05)	0.69 (0.18)	0.53 (0.96)	1.22 (1.23)	0.91 (0.05)	-0.53 (0.71)	0.24 (0.11)	0.03 (0.01)	0.08 (0.07)

Table 4: Estimated shocks parameters - std. errors in parentheses

The elements of ζ_2 are chosen to minimize the weighted distance of the model IRFs, $\Gamma(\zeta_2)$, from the VAR IRFs, Γ:

$$\zeta_2^* = \arg\min_{\zeta_2} \left(\Gamma - \Gamma(\zeta_2)\right)' \Psi^{-1} \left(\Gamma - \Gamma(\zeta_2)\right),$$

where Ψ is a diagonal matrix containing the variances of the estimated VAR impulse response functions. The loss function above attributes more weight to the impulse response functions estimated more precisely.[27]

The parameter estimates are reported in Tables 3 and 4. They are broadly consistent with the estimates reported by Altig et al. (2002). The estimated Calvo parameters imply an average price contract duration of 2.17 and 4.26 quarters for firms in the consumption and investment goods sectors, respectively. The average wage contract duration is 3.72 quarters.

The model impulse responses to a monetary policy shock are remarkably close to the responses in the VAR. The IRFs to technology shocks are reasonably close to those found in the data (see Figures 2 and 3).

4.3 Comovement

Table 5 displays comovement statistics for the simulated model and the corresponding statistics for U.S. data.

The contemporaneous correlations of sectoral labor inputs with aggregate output in the model are positive and close to the corresponding values for the data. The model understates the relative volatility of labor in the investment goods sector. The model generates a countercyclical wedge between the wage rate and the marginal rate of substitution between consumption and leisure.[28] The wedge in the data is measured as

$$\tilde{\gamma}_t = \tilde{w}_t - \left(\tilde{c}_t + \tilde{l}_t\right),$$

where $\tilde{w}$ is the real wage, $\tilde{c}$ is real consumption, and $\tilde{l}$ denotes hours worked (all of which have been logged and HP_{1600} filtered). The business cycle properties of the model's wedge are similar to the properties of its empirical counterpart.

[27] This explains why the estimated model does a better job at reproducing responses to monetary shocks than to technology shocks.

[28] The model implies a more complicated expression for the wedge, due to the presence of habit persistence. Taking this into account does not change the results in Table 5.

	x	$\sigma_x/\sigma_{\tilde{y}}$	$\rho_{x,\tilde{y}}$				
			-2	-1	0	1	2
Model	$\tilde{l}_C$	0.82 [0.53, 0.95]	0.80 [0.50, 0.93]	0.89 [0.59, 0.98]	0.88 [0.59, 0.97]	0.77 [0.50, 0.86]	0.58 [0.35, 0.69]
	$\tilde{l}_I$	1.71 [1.07, 2.22]	0.63 [0.33, 0.82]	0.78 [0.47, 0.93]	0.84 [0.54, 0.97]	0.82 [0.52, 0.95]	0.72 [0.42, 0.88]
	$\tilde{\gamma}$	1.43 [0.95, 1.64]	−0.80 [−0.45, −0.89]	−0.92 [−0.56, −0.98]	−0.94 [−0.61, −0.99]	−0.86 [−0.54, −0.92]	−0.69 [−0.4, −0.78]
U.S. data	$\tilde{l}_C$	0.74	0.79	0.87	0.85	0.68	0.46
	$\tilde{l}_I$	2.44	0.80	0.89	0.88	0.71	0.48
	$\tilde{\gamma}$	1.53	−0.48	−0.68	−0.84	−0.82	−0.71

Table 5: Comovement statistics.
$\sigma_x/\sigma_{\tilde{y}}$ is the std. dev. of variable x relative to output, $\tilde{y}$. $\rho_{x,\tilde{y}}$ is the cross-correlation of variable x_{t+j}, $j=-2,...,2$ with output, $\tilde{y}_t$.
U.S. data statistics were computed on logged and HP-filtered data. Model statistics are averages over 1,000 model simulations computed on HP-filtered series; 2.5^{th} and 97.5^{th} percentile are in brackets.

Table 6 reports the relative volatility of sectoral labor with respect to output and the contemporaneous correlation with output for various versions of the model.[29] The baseline model refers to the model where all frictions are operative. The other versions of the model are characterized as follows:

- no habits: $b = 0$;
- flexible prices: $\xi_{p,C} = \xi_{p,I} = 0$;
- flexible wages: $\xi_w = 0$;
- low investment adjustment costs: $\kappa = 0.05$;
- no variable capital utilization: $\sigma_a = 10,000$;
- no fixed production costs: $\lambda_f = 1$;

[29] See footnote 24.

- no working capital: firms in the intermediate good sectors do not need to borrow their working capital, so that the unit labor cost is simply the wage rate; the loan-market-clearing equation is modified accordingly;
- frictionless economy: all of the above and monetary policy does not respond to technology shocks, i.e., $\rho_{\mu_j} = c_{\mu_j} = l_{\mu_j} = 0$, $j = C, I$.

The other parameters are kept fixed at their estimated values.

Demand shocks (i.e., monetary policy shocks) generate comovement independently of the frictions included in the model. A lower interest rate stimulates demand for both consumption and investment goods.[30] With unchanged technology, the only way to satisfy the increased demand is to use more inputs in both sectors.

The frictionless economy displays the comovement puzzle. Technology shocks of either kind induce a negative correlation between labor used in the consumption goods sector and aggregate activity.

The key friction in generating comovement in response to technology shocks is sticky wages. The model with flexible wages generates significantly lower correlations of l_C and l_I with output in response to any shock. The flexible wages model simulated with the three shocks together displays a correlation for l_C that is less than one third of the correlation in the baseline model. The correlation of l_I with aggregate activity is close to zero. Also, the wedge between consumption and leisure is acyclical when wages are flexible, while it remains strongly countercyclical for the other versions of the model (see Table 7).

Habit formation plays a minor role in delivering comovement in response to embodied technology shocks. The model without habits displays a substantial amount of comovement when all the shocks are considered. This is in contrast with the results of Boldrin et al. (2001), where habit formation is essential to generate comovement. They present a two-sector model driven by neutral technology shocks, with immobile capital and labor, and habit persistence. In response to technology shocks, labor cannot be relocated from the consumption goods to the investment goods sector. In subsequent periods, agents persist in consuming at the relatively higher level because of habits. Boldrin et al. (2001) obtain comovement by combining habit formation with the sector-specificicity of productive factors for one period in a model with flexible prices and wages. In this paper nominal wage rigidities

[30] This effect is close to zero for the frictionless economy.

	$\sigma_{\tilde{l}_C}/\sigma_{\tilde{y}}$				$\sigma_{\tilde{l}_I}/\sigma_{\tilde{y}}$			
Model	E	N	M	All	E	N	M	All
Baseline	0.86	0.81	0.83	0.82	2.24	0.86	2.20	1.71
No habits	1.12	1.14	1.12	1.10	1.90	0.33	1.77	1.39
Flexible prices	0.88	0.82	0.84	0.83	2.10	1.10	2.18	1.78
Flexible wages	1.58	0.43	0.96	0.51	5.83	3.04	3.33	3.07
Low inv. adj. costs	0.54	0.67	0.53	0.57	3.15	1.41	3.10	2.69
No var. capital util.	0.94	0.62	0.84	0.71	3.26	1.53	2.57	2.06
No fixed prod. cost	1.22	1.06	1.17	1.11	2.72	0.75	2.66	1.97
No working capital	0.85	0.85	0.85	0.85	2.16	1.96	2.14	2.07
Frictionless	0.85	0.41	0.02	0.41	4.86	2.12	0.11	2.13
U.S. data	0.74				2.44			
	$\rho_{\tilde{l}_C,\tilde{y}}$				$\rho_{\tilde{l}_I,\tilde{y}}$			
Model	E	N	M	All	E	N	M	All
Baseline	0.95	0.81	0.96	0.88	0.98	0.81	0.98	0.84
No habits	0.94	0.72	0.94	0.83	0.92	−0.27	0.88	0.64
Flexible prices	0.96	0.84	0.96	0.90	0.99	0.83	0.99	0.89
Flexible wages	0.57	0.33	0.65	0.34	−0.19	0.11	0.42	0.12
Low inv. adj. costs	0.93	0.77	0.92	0.85	0.99	0.54	0.99	0.86
No var. capital util.	0.95	0.67	0.97	0.78	0.97	0.69	0.97	0.78
No fixed prod. cost	0.96	0.77	0.97	0.85	0.98	0.74	0.97	0.78
No working capital	0.96	0.96	0.97	0.96	0.99	0.98	0.99	0.99
Frictionless	−0.41	−0.25	0.02	−0.24	0.43	0.27	0.02	0.27
U.S. data	0.85				0.88			

Table 6: Sectoral labor statistics for various versions of the model
$\sigma_x/\sigma_{\tilde{y}}$ is the std. dev. of variable x relative to output, $\tilde{y}$. $\rho_{x,\tilde{y}}$ is the correlation of variable x with output, $\tilde{y}$.
U.S. data statistics were computed on logged and HP-filtered data. Model statistics are averages over 1,000 model simulations computed on HP-filtered series driven by embodied tech. shock (E), neutral tech. shock (N), monetary shock (M), and all 3 shocks.

Model	$\sigma_{\tilde{\gamma}}/\sigma_{\tilde{y}}$	$\rho_{\tilde{\gamma},\tilde{y}}$
Baseline	1.37	−0.90
No habits	1.81	−0.84
Flexible prices	1.44	−0.92
Flexible wages	0.91	0.01
Low investment adj. costs	1.23	−0.91
No variable capital util.	1.58	−0.79
No fixed prod. cost	1.64	−0.86
No working capital	1.48	−0.98
U.S. data	1.53	−0.84

Table 7: Wedge statistics for various versions of the model
$\sigma_{\tilde{\gamma}}/\sigma_{\tilde{y}}$ is the std. dev. of the wedge relative to output, $\tilde{y}$. $\rho_{\tilde{\gamma},\tilde{y}}$ is the correlation of the wedge with output, $\tilde{y}$.
U.S. data statistics were computed on logged and HP-filtered data. Model statistics are averages over 1,000 model simulations computed on HP-filtered series.

generate comovement, while capital and labor can be freely moved across sectors.

Jin and Zeng (2002) focus on the working capital channel in a limited-participation model as a rationalization of the comovement puzzle. The nominal interest rate decreases in response to both monetary policy shocks and neutral technology shocks. The general equilibrium effect of technology shocks on the nominal interest rate is due to an increase in the desired amount of savings. The reduced unit labor cost for firms in both sectors is responsible for comovement in their model. A similar channel operates in my model, but it is not essential for generating comovement.

The results in Tables 6 and 7 are robust to re-estimating the constrained versions of the model described above.[31] In particular, an estimated flexible-wage model does a much poorer job at matching the responses to shocks, it generates correlations of sectoral labor inputs with output that are 50% smaller than the corresponding correlations in the data, and it produces an acyclical wedge. The results in Tables 6 and 7 are robust to the use of a band-pass filter (see Christiano and Fitzgerald, 2003) to extract the cyclical component of the series with period between two and eight years.

5 Conclusions

The analysis in this paper is similar, in spirit, to the RBC literature. In the RBC literature a model is parametrized using independent information, and it is evaluated by assessing its capability to reproduce second moments of aggregate data.

My model has been parametrized by estimating the relevant parameters, instead of calibrating them, without using sectoral input variables. The model is consistent with the literature in terms of its ability to produce responses to neutral technology shocks and monetary policy shocks that are similar to those obtained in a VAR representation of U.S. data. In addition, the model is an empirically plausible account of the effects of investment-specific technology shocks. The estimated model is then simulated to assess its ability to reproduce second moments of the sectoral inputs that we observe in the data.

[31] The model without capital-adjustment costs and the frictionless economy are so impaired in matching the VAR impulse response functions that they could not be estimated.

The model presented in this paper succeeds in generating comovement, a major hurdle for standard models. Sticky wages are the key friction in generating comovement. Nominal wage rigidities create a countercyclical markup of the real wage on the marginal rate of substitution between consumption and leisure. Moreover, this wedge has the same business cycle properties as its empirical counterpart. The wage markup, by keeping the cost effect of productivity shocks smaller than the demand effect, is responsible for comovement of sectoral inputs.

The modeling of sticky wages is admittedly very stylized. I interpret the evidence on the importance of nominal wage rigidities[32] as a starting point for further research.

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A Data

Table 8 describes the raw data used in the paper and provides the corresponding Haver mnemonics. The data are readily available from other commercial

[32] Other authors, in different contexts, have pointed to the importance of wage rigidities. Christiano et al. (2005) argue that the use of sticky wages is important for obtaining a persistent response of inflation to monetary policy shocks without having to rely on inplausible amounts of price stickiness. Hall (2005) shows how wage rigidities deliver plausible volatility for unemployment, job-finding rates, and vacancies.

(e.g., DRI-WEFA) and non-commercial (e.g., the St. Louis FRB database FREDII) databases, as well as from the original sources (BEA, BLS, Board of Governors of the FRS).

The monetary aggregate used is money zero maturity (after 1974), spliced with M2 minus small time deposits (before 1974).[33]

The remaining variables used in the VAR analysis are constructed from the raw data in the obvious way:

$$\frac{Y}{l} = \frac{\text{GDPH/LN16N}}{\text{LXFNH/LN16N}},\ \pi = 4\Delta\log\left(\text{JGDP}\right),\ \frac{w}{Y/l} = \frac{\text{LXNFC}}{\text{JGDP}}\frac{1}{Y/l},$$
$$u = \text{CUMFG},\ l = \frac{\text{LXFNH}}{\text{LN16N}},\ \frac{C}{Y} = \frac{\text{CN+CS+G}}{\text{GDP}},\ \frac{I}{Y} = \frac{\text{CD+I}}{\text{GDP}}.$$

The variables used for constructing comovement statistics in Table 1 are constructed as follows:

$$c = \frac{\text{CN+CS+G}}{\text{JGPD}\times\text{LN16N}},\ l_C = \frac{\text{LRDURGA}\times\text{LADURGA}}{\text{LN16N}},$$
$$i = \frac{\text{GCD+GPI}}{\text{JGPD}\times\text{LN16N}},\ l_I = \frac{\text{LRNDURA}\times\text{LANDURA+LRPSRVA}\times\text{LAPSRVA}}{\text{LN16N}},$$
$$y = \frac{\text{GDPH}}{\text{LN16N}},\ l = l_C + l_I.$$

A.1 Price of Investment

The deflator for investment goods is constructed following Gordon (1990), Cummins and Violante (2002), and Fisher (2006).

I first extrapolated forward the time series models fitted by Cummins and Violante (2002) to construct updated annual quality-adjusted deflators for equipment and software and the durables component of personal consumption expenditures. The fixed investment deflator is obtained by chainweighting the equipment and software deflator I constructed with the deflator for nonresidential structures from NIPA. Chainweighting the fixed investment and the residential investment deflator from NIPA gives the gross private domestic investment (GPDI) deflator. Finally, the investment deflator is constructed by chainweighting the GPDI deflator and the deflator for personal consumption expenditures on durables.

[33] I am grateful to Larry Christiano for suggesting the use of this monetary aggregate.

Variable	Units	Haver (USECON)
Civilian Noninstitutional Population	Thousands	LN16N
Nominal GDP	Bil. $, SAAR	GDP
Real GDP	Bil. Chn. 2000 $, SAAR	GDPH
GDP: Chain Price Index	Index, 2000=100, SA	JGDP
PCE: Nondurable Goods	Bil. $, SAAR	CN
PCE: Services	Bil. $, SAAR	CS
PCE: Durable Goods	Bil. $, SAAR	CD
GPDI	Bil. $, SAAR	I
Gov't Cons. Exp. & Gross Inv.	Bil. $, SAAR	G
Federal Funds (effective) Rate	% p.a.	FFED
Hours of all persons (Nonfarm Bus. Sector)	Index, 1992=100, SA	LXNFH
Avg. weekly hours (Durable Goods Mfg.)	Hours, SA	LRDURGA
Avg. weekly hours (Nondurable Goods Mfg.)	Hours, SA	LRNDURA
Avg. weekly hours (Priv. Service-providing ind.)	Hours, SA	LRPSRVA
All Employees (Durable Goods Mfg.)	Thousands, SA	LADURGA
All Employees (Nondurable Goods Mfg.)	Thousands, SA	LANDURA
All Employees (Priv. Service-providing ind.)	Thousands, SA	LAPSRVA
Compensation per hour (NBS)	Index, 1992=100, SA	LXNFC
Capacity utilization (manufacturing)	% of capacity, SA	CUMFG
Money Stock: MZM	Bil. $, SA	FMZM
Money Stock: M2	Bil. $, SA	FM2
Money Stock: Small Time Deposits	Bil. $, SA	FMSTT

Table 8: Raw data

The result of this procedure is an annual time series for the investment deflator. As in Fisher (2006), I construct a quarterly time series by interpolating the annual deflator with the quarterly deflator for the same aggregate constructed exclusively from NIPA data.

The relative price of investment, p_I, is the investment deflator divided by the GDP deflator (JGDP).

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