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Understanding the Puzzling Effects of Technology Shocks**

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A Defense of RBC: Understanding the Puzzling Effects of Technology Shocks*

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Abstract

The research led by Gali (AER 1999) and Basu et al. (AER 2006) raises two important questions regarding the validity of the RBC theory: (i) How important are technology shocks in explaining the business cycle? (ii) Do impulse responses to technology shocks found in the data reject the assumption of flexible prices? This paper argues that the conditional impulse responses of the U.S. economy to technology shocks are not grounds to reject the notion that technology shocks are the main driving force of the business cycle and the assumption of flexible prices, in contrary to the conclusions reached by the literature.

Keywords: RBC, Technology Shocks, Aggregate Production Function, Entry and Exit, Sticky Prices, Demand Rigidity, Business Cycle.

JEL codes: E31, E32, E52.

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1 Introduction

Because of intertemporal substitutions and instantaneous market clearing, standard RBC models imply a sharp rise in aggregate labor and investment, as well as the real interest rate, immediately after an aggregate technology shock. However, Gali (1999) and Basu et al. (2006) found that aggregate technology shocks in the U.S. economy are contractionary to labor, investment and the real interest rate in the short run. This finding has two important implications regarding the validity of the RBC theory: (i) aggregate technology shocks may not be the main driving force of the business cycle because aggregate labor and investment are procyclical in the data; (ii) aggregate supply is not responsive to technology shocks in the short run, suggesting sticky prices. These implications have led this literature to conclude that RBC theory is dead (see, e.g., Francis and Ramey, 2005).

It is possible that technology shocks are not important and prices are sticky. However, based on the above findings alone one cannot logically conclude that this is indeed the case in reality. Whether or not technology shocks are an important driving force of the business cycle does not follow logically from the sign of the initial impulse responses to technology shocks. Two time series can still be positively correlated at the business cycle frequency even if they have the opposite signs of impulse responses on impact.¹

The importance of technology shocks notwithstanding, a contractionary effect of technology shocks on aggregate inputs and factor prices does not reject flexible prices. This point is the main focus of the paper.

Based on the "purified" technology series estimated by Basu et al. (2006), we confirm that both aggregate technology shocks and sector-specific technology shocks are contractionary on sectorial activities. However, sectorial inputs decrease only temporarily under aggregate technology shocks but permanently under sector-specific technology shocks. In other words, while aggregate technology progress is contractionary in the short run, sector-specific technological progress tends to be contractionary in both the short run and the long run. We show that these stylized facts are fully consistent with a flexible-price RBC with firm entry and exit.

Our RBC model with firm entry and exit is motivated by the fact that aggregate net business formation is strongly procyclical under aggregate technology shocks, suggesting the number of firms is an important margin for aggregate output and inputs to adjust under business cycle

¹For example, two sine curves with a phase difference may still comove together despite opposite signs at the origin.

shocks. Since this margin of capacity adjustment lies only at the aggregate level but not at the firm level, aggregate technology shocks and firm-level technology shocks should have asymmetric implications for resource allocation and economic fluctuations. We illustrate this intuition using a perfectly competitive flexible-price RBC model in which the number of firms is a key propagation mechanism of aggregate technology shocks.

Francis and Ramey (2005) show that a flexible-price RBC model with aggregate demand rigidity (namely, habit formation and investment adjustment costs) can also generate short-run negative responses of labor to technology shocks. Assuming a Leontief aggregate production technology (with labor and capital as perfect complements) can achieve similar result. But these models with aggregate rigidities are not able to generate short-run negative responses of investment to technology shocks, which is one of the key stylized facts of the U.S. economy emphasized by Basu et al.²

Our model does not suffer from this shortcoming. In addition, the dynamics of the real wage and the real interest rate under technology shocks are emphasized by Francis and Ramey (2005), Basu et al. (2006), and Liu and Phanuef (2007) as important litmus tests for business cycle models. In the data, a positive aggregate technology shock leads to a modest rise in the real wage on impact and a permanent rise in the long run, and a sharp decrease in the real interest rate in the short run. These stylized facts are viewed by this literature as consistent with sticky prices and/or sticky wages, but not with flexible prices and wages. However, our model is consistent with the dynamic behavior of the real wage and the real interest rate despite the lack of price-wage sickness in the model. We view this as an advantage of our model because sticky price models imply a systematic positive relationship between the degree of price stickiness and the extent of the contractionary effects of technology shocks on hours. Empirical evidence at the industry level for the existence of such a relationship is absent (see Chang and Hong, 2006).

Our approach draws inspiration from the existing literature by emphasizing rigidity in factor demand. However, we build demand rigidity into the micro level without assuming demand rigidities at the aggregate level. A micro-level rigidity in factor demand can arise from a Leontief production structure at the firm level due to fixed capacities. Such a micro structure is consistent with standard aggregate production technologies with positive elasticity of substitution across aggregate inputs (see, e.g., Houthakker 1955-56, Johansen 1972, and Lucas 1970). Since the number of firms can vary due to entry and exit, our model with micro-level rigidity is identical to

²There is a fast growing literature regarding the dynamic effects of technology shocks. See, for example, Basu (1998), Basu et al. (2002, 2006), Chang and Hong (2006), Chari et al. (2005), Christiano et al. (2004, 2006), Fernald (2005), Francis and Ramey (2005), Gali (1999), Gali et al. (2003), Gali and Rabanal (2004), Liu and Phanuef (2006), Ramey (2004) and Vigfusson (2004), among many others.

a standard frictionless RBC model in aggregate dynamics, everything else equal. In this case, permanent aggregate technology shocks generate immediate positive responses of aggregate investment and labor; which is inconsistent with the data. However, if firms must wait for one period to produce (or to earn profits) after entry due to time-to-build, then the model starts to behave very differently from standard frictionless RBC models and is able to explain all of the aforementioned facts about the puzzling effects of aggregate and sector-specific technology shocks. Hence, time-to-build is the only assumption we need in order to break the equivalence of aggregate dynamics between our model and a standard frictionless RBC model, despite demand rigidities at the micro level. In fact, many standard aggregate production functions, such as the Dixit-Stiglitz function with constant returns to scale and constant elasticity of substitution (CES) across aggregate inputs, can be derived as special cases from our model with micro-level rigidity and firm's entry-and-exit. Hence the assumption of a Leontief structure at the firm level is innocuous. In light of this, our approach provides a micro foundation for standard RBC models which assume CES aggregate production technologies.³

The rest of the paper proceeds as follows. Section 2 presents stylized facts about the dynamic effects of technology shocks on aggregate and sectorial activities. These stylized facts appear to be profoundly inconsistent with RBC models with flexible prices. However, in Sections 3-5, we show this is not the case: RBC models with perfect competition and instantaneous market clearing are fully consistent with the stylized facts. A simple one-sector benchmark model is presented in Section 3 to gain intuition, and a full model with multiple sectors and heterogeneous firms is presented in Sections 4-5. Section 6 shows that our model with firm entry and exit based on a Leontief structure of firms provides a general-equilibrium micro foundation for standard aggregate production functions with constant returns to scale and constant elasticity of substitution across aggregate inputs. Our approach also provides an explanation for the total factor productivity (TFP), alternative to the labor search approach of Lagos (2006). Section 7 concludes.

2 Stylized Facts

In this section, we replicate three sets of stylized facts (Basu et al.) regarding the dynamic effects of technology shocks. First, in the initial period after an aggregate technology shock, aggregate consumption rises, aggregate output and net business formation do not change significantly,

³The strategy of relying on a micro-level Leontief structure to derive standard aggregate production functions is also used by Lagos (2006) to study the micro foundations of aggregate TFP. However, since Lagos (2006) uses a labor search model, the conditions for deriving aggregate production functions in his approach are very different from ours.

while aggregate investment and labor decline sharply. In the longer run, however, all variables increase permanently. Second, sectorial output does not change significantly while sectorial inputs decrease significantly in the initial period after an aggregate technology shock; but they all rise permanently in the longer run. Third, under sector-specific technology shocks, sectorial output does not change significantly (either in the short run or in the long run), but sectorial inputs decrease both in the short run and in the long run. These stylized facts are robust to various methods of estimation and identification. They suggest that aggregate technology shocks are contractionary in the short run but expansionary in the long run at both aggregate and sectorial levels, but sector-specific technology shocks are contractionary for sectorial activity in both the short run and the long run.

Estimation Method. All variables are defined in growth rates. Time series representing "technology shocks" are taken from Basu et al. Three alternative methods are used to identify innovations in the technology series and to generate impulse responses from the U.S. economy. The first approach follows Basu et al. by assuming that the estimated technology series are completely exogenous. Namely, we estimate a restricted bi-variate VAR for the technology series (x) and another variable under interest (y):

$$\begin{pmatrix} 1 & 0 \\ -c_0 & 1 \end{pmatrix} \begin{pmatrix} x_t \\ y_t \end{pmatrix} = \begin{pmatrix} a_1 & 0 \\ c_1 & b_1 \end{pmatrix} \begin{pmatrix} x_{t-1} \\ y_{t-1} \end{pmatrix} + \begin{pmatrix} a_2 & 0 \\ c_2 & b_2 \end{pmatrix} \begin{pmatrix} x_{t-2} \\ y_{t-2} \end{pmatrix} + \begin{pmatrix} \varepsilon_t \\ v_t \end{pmatrix}, \quad (1)$$

where $\{a, b, c\}$ are OLS coefficients and ε is the innovations to technology. This restricted VAR implies that ε explains one hundred percent of the variance in the technology series (x). Notice that ε and v are orthogonal by construction.⁴ The second and third approaches do not assume one hundred percent exogeneity of the estimated technology series and are based on an unrestricted VAR:

$$\begin{pmatrix} x_t \\ y_t \end{pmatrix} = \begin{pmatrix} a_1 & d_1 \\ c_1 & b_1 \end{pmatrix} \begin{pmatrix} x_{t-1} \\ y_{t-1} \end{pmatrix} + \begin{pmatrix} a_2 & d_2 \\ c_2 & b_2 \end{pmatrix} \begin{pmatrix} x_{t-2} \\ y_{t-2} \end{pmatrix} + \begin{pmatrix} e_{xt} \\ e_{yt} \end{pmatrix}, \quad (2)$$

where e_x and e_y are OLS residuals with covariance matrix Σ . To identify innovations to technology, we use both the Cholesky decomposition and the Blanchard-Quah (1989) method, respectively, to construct the mapping:

$$\begin{pmatrix} e_{xt} \\ e_{yt} \end{pmatrix} = \begin{pmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{pmatrix} \begin{pmatrix} \varepsilon_t \\ v_t \end{pmatrix}, \quad (3)$$

⁴The second projection in Equation (1) implies v_t is orthogonal to $\{x_t, x_{t-1}, x_{t-2}\}$. Hence it must also be orthogonal to $\varepsilon_t = x_t - a_1x_{t-1} - a_2x_{t-2}$.

where ε is the identified innovation to technology (orthogonal to the innovation v). The variance of both innovations is normalized to one. Thus, the above mapping implies $\Sigma = \Gamma\Gamma'$. Under the Cholesky decomposition, Γ is triangular with $\gamma_{12} = 0$. Under the Blanchard-Quah method, in the moving average representation, $x_t = \sum_{j=0}^{\infty} \alpha_j \varepsilon_{t-j} + \sum_{j=0}^{\infty} \beta_j v_{t-j}$, the long-run restriction, $\sum_{j=0}^{\infty} \beta_j = 0$, is imposed so that only ε can have permanent effect on x . The results are very similar under the three different approaches, which help to establish the robustness of the stylized facts we try to document.

Data. All sectorial data are from Basu et al. (2006). The aggregate technology series is constructed as the weighted average of sectorial technology series (see Basu et al.). Aggregate output, consumption, and investment are taken from the Bureau of Economic Analysis. Aggregate employment and hours are taken from the Bureau of Labor Statistics. Net business formation is taken from the Department of Commerce (Bureau of the Census) and Dun & Bradstreet, Inc. To be consistent with technology series from Basu et al., all data are annual averages and are truncated to match the sample period of 1949-1996.⁵

2.1 Impulse responses to aggregate technology shocks

Figure 1 displays the impulse responses of aggregate output, net business formation, consumption, investment and hours to an aggregate technology shock. The shaded area in each window represents one-standard deviation bands.

⁵Output is defined as real GDP, consumption as total real consumption, investment as total non-residential fixed investment. All data are measured as year over year percentage change (Table 1.1.1 from BEA). Labor statistics include total nonfarm employees and total private average weekly hours of production workers. Both data are monthly. In forming the year over year growth rate, we use the monthly average of each year, consistent with Basu et al. (2007). Since data on hours are not available before 1964, we have also included total nonfarm employees in figure 1 (panel 5). The real wage is the ratio of the nominal hourly wage and the consumer price index (CPI). The real interest rate is the difference between the federal funds rate and the CPI inflation rate.

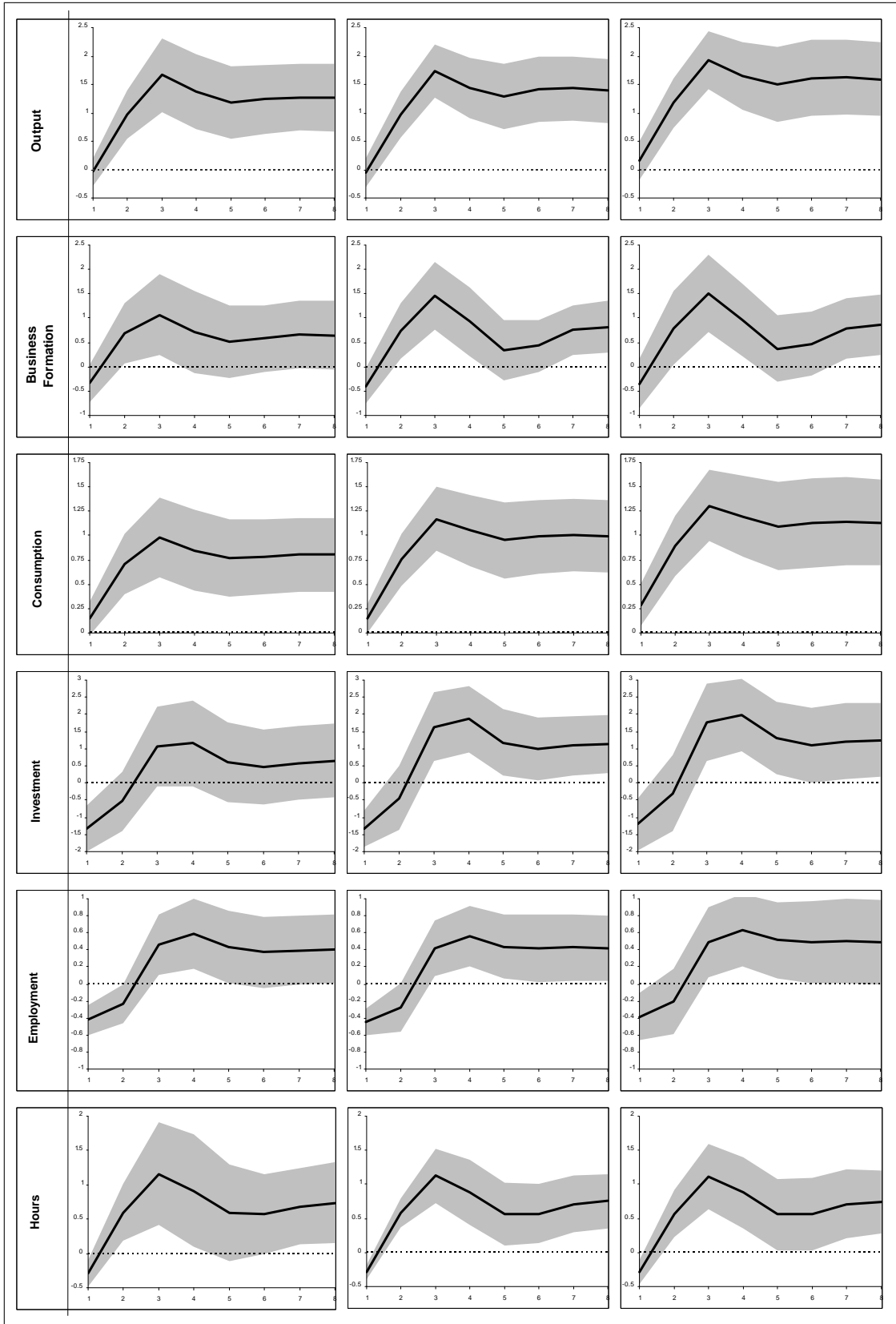


Figure 1. Impulse Responses to Aggregate Technology Shock.

The first column shows estimations based on the restricted VAR of Basu et al. The second and third columns show estimations based on the Cholesky and Blanchard-Quah methods, respectively. After a technology shock, GDP does not respond significantly on impact but increases permanently afterwards. Net business formation declines slightly on impact but increases (co-move with output) in the future. Consumption rises on impact and rises further subsequently towards its long-run steady state. Investment and employment both decline sharply on impact, but then rise significantly in the longer run. Similarly, hours decline sharply on impact but increase strongly with a lag. These dynamic patterns of impulse responses are consistent with the findings of Basu et al. (2006).⁶

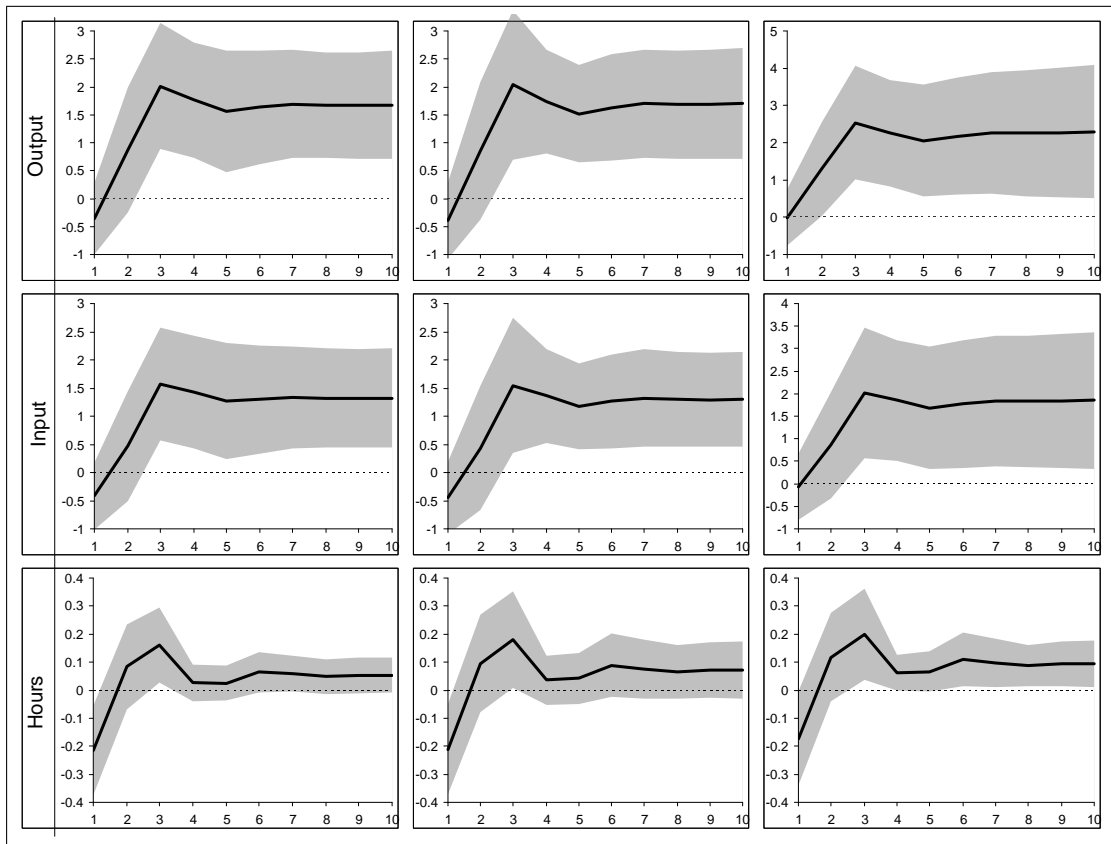


Figure 2. Sectorial Responses to Aggregate Technology Shock.

Figure 2 shows the impulse responses of sectorial output and sectorial inputs to aggregate technology shocks. As before, the three columns correspond to the three different methods of shock identification. In each window, the solid line represents the average of all 29 sectors' impulse responses and the shaded area represents one standard deviation bands across sectors. The first panel pertains to output, the third panel pertains to hours, and the middle panel to

⁶When the total factor productivity is purified using the method of Basu et al., Chang and Hong (2006) obtain similar results with respect to the impact of technology shocks on hours.

other inputs (e.g., capital and employment).⁷ The pictures show that the effects of aggregate technology shocks on sectorial output and inputs broadly mimic those on aggregate output and inputs. Namely, in the initial period after the shock sectorial output does not change significantly but sectorial inputs (especially hours) tend to decline sharply. However, output and inputs all increase permanently in the longer run.

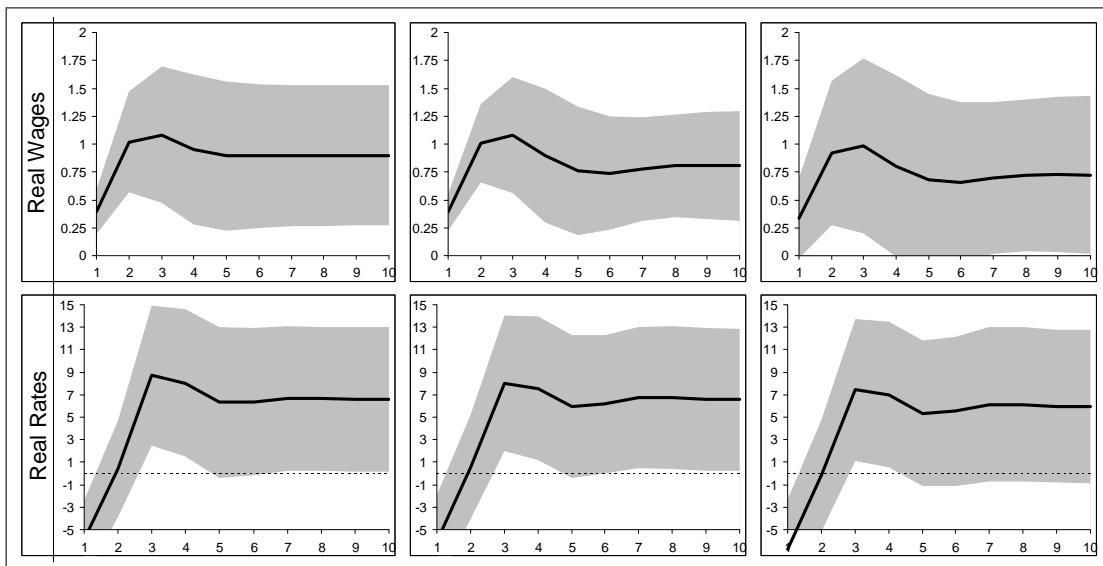


Figure 3. Impulse Responses of Real Wage and Real Rate.

Figure 3 shows the impulse responses of the real wage and the real interest rate to technology shocks. The most striking difference between the two series is that the real wage increases while the real rate decreases on impact after a technology shock. Since the real factor price is proportional to the output-factor ratio times the real marginal cost, and since output (as well as the capital stock) do not respond significantly in the initial period after the shock, the short run behavior of the real wage and the real interest rate imply that the real marginal cost must decrease under technology shocks but no more than the decrease in hours. This imposes a severe constraint and discipline on a business cycle model. Standard RBC models with constant marginal cost are inconsistent with such dynamic behaviors of factor prices.⁸ Also notice the dramatic difference in the magnitude of the responses of the two factor prices: the real interest rate is about 10 times more volatile than the real wage. This is obviously consistent with models where labor is more responsive than capital to technology shocks, provided that one important condition is met: the negative response of marginal cost to technology shocks must

⁷In the data of Basu et al., there are two types of inputs: i) hours worked, and ii) all else (including intermediate goods, capital and labor, etc.).

⁸For example, a model with habit formation and investment adjustment cost implies positive response of the real interest rate on impact.

be highly transitory. In the initial period, labor decreases but the capital stock does not move, hence the decline in the marginal cost brings down the real interest rate more than the real wage. If changes in the marginal cost are highly transitory, then as output increases in the intermediate run, the closer comovement of labor than capital to output will render the real wage to increase less than the real interest rate. In other words, the real interest rate would not increase more than the real wage in the longer run if the initial decrease in marginal cost were highly persistent under permanent technology shocks.

2.2 Impulse responses to sector-specific technology shocks

Measure of sector-specific technology shocks. Ideally, a sector-specific technology shock process should be orthogonal not only to aggregate technology shocks but also to the sector-specific technology shocks in other sectors of the economy. However, the measures of sectorial technology of Basu et al. do not satisfy these criteria for two reasons. First, the aggregate technology series of Basu et al. is constructed as a weighted average of the sectorial technology series, hence is correlated with all sectorial technology series by construction. Second, the sectorial technology series are not orthogonal among each other. Given the short sample period of the data (48 observations in each series) and the relatively large number of sectors (29 sectors), it is problematic to construct sector-specific technology shocks as residuals of regressing each sectorial technology series on the other 28 sectorial series and the aggregate series as dependent variables, due to potential colinearity problem. In this paper, we purify the sectorial technology series of Basu et al. as much as we can by regressing each sectorial series on its own lag and the aggregate technology series.⁹ Although this purification procedure does not necessarily yield orthogonality among the "purified" sector-specific technology shock processes, it does improve the degree of purity by ensuring orthogonality with the aggregate technology of all sectors. However, since the constructed "sector-specific" technology shocks are not necessarily orthogonal among each possible pair of sectors, the degree of purity can only be judged by the average correlations among these series.

Figure 4 shows the distribution of correlations between any two series of purified sector-specific technology shocks. Since there are 29 sectors in our sample, there are 406 possible pair-wise combinations. The histogram of the 406 correlations in Figure 3 shows that the constructed sector-specific technology shock series are not pair-wise orthogonal. The maximum correlation is 0.8 and the minimum correlation is -0.6 . However, the distribution is approximately normal with the mass centering around zero (the mean of the correlations is 0.04). Given this, although

⁹The results are very similar when the lagged variable is excluded.

the technology shock series are not 100 percent "sector-specific", they have on average zero correlations across sectors. Hence, regarding the dynamic effects of sector-specific technology shocks on sectorial activities, the average impulse responses across all sectors maybe more informative than the individual impulse responses.

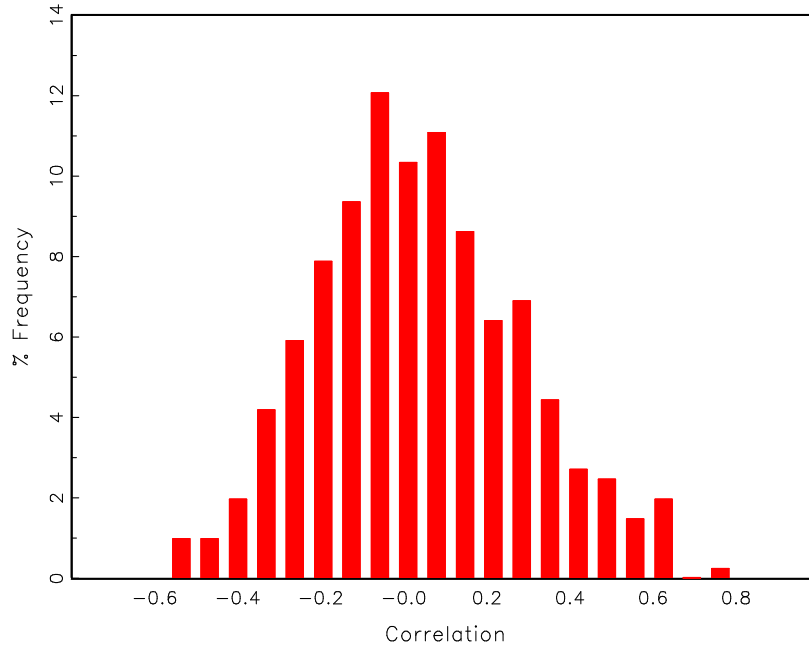


Figure 4. Distribution of Correlations among Sector-Specific Technology Shocks.

Figure 5 shows the impulse responses of sectorial output and inputs to sector-specific technology shocks of the same sector, where solid lines represent the average impulse response and the shaded area represents one standard deviation from the mean across sectors. As before, in each panel the first column corresponds to the method of Basu et al., the second and the third columns correspond to Cholesky decomposition and the method of Blanchard and Quah, respectively. The first panel shows that on average, sector-specific technology shocks have little impact on sectorial output in both the short run and the long run (especially under the method of Basu et al.). This is in sharp contrast to the effects of aggregate technology shocks shown in Figure 2. The second and the third panel show that sector-specific technology shocks are contractionary to sectorial inputs in both the short and the long run, which is also in sharp contrast to the effect of aggregate technology shocks shown in Figure 2 above.

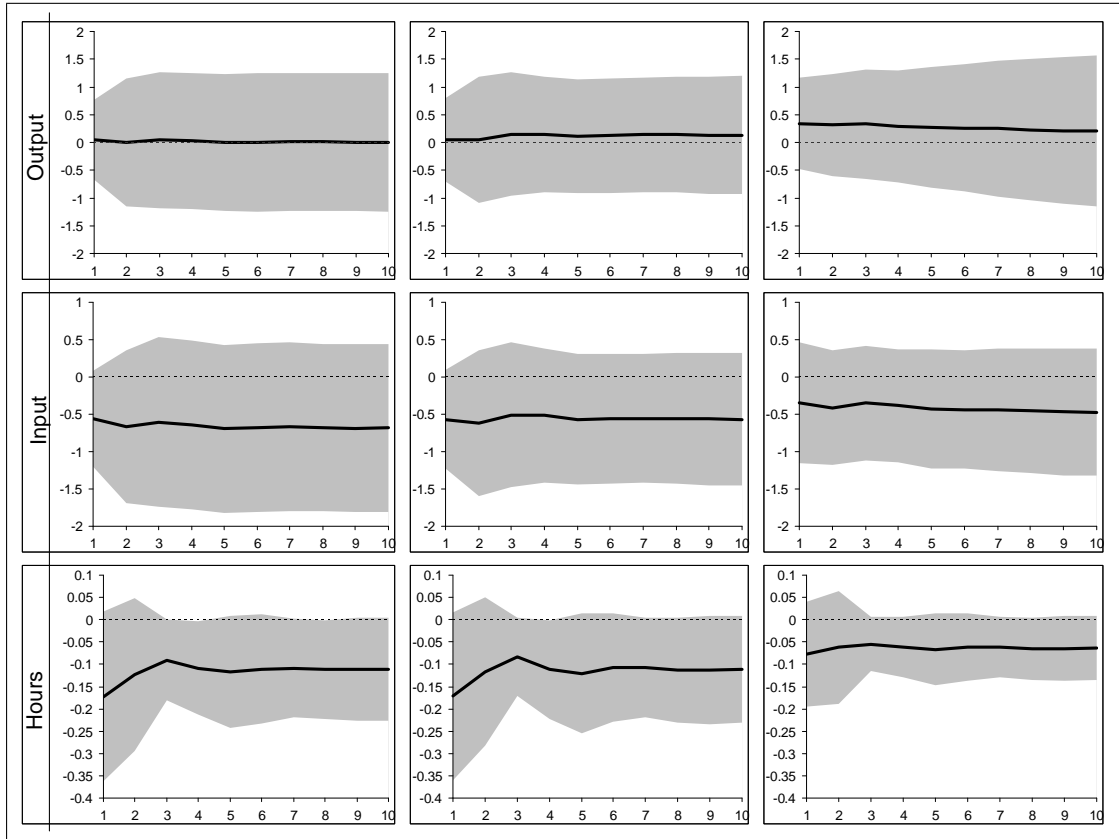


Figure 5. Sectorial Responses to Sector-Specific Technology Shock.

Intuitively, the permanent contractionary effects of sector-specific technology shocks on sectorial inputs make sense because it would be in firms' best interest to permanently reduce expenditures on inputs when output could not be changed. Hence, the fundamental question is why sectorial output remains essentially unchanged over time under sector-specific technology shocks, but rises sharply in the longer run under aggregate technology shocks?

Our approach to answer this question is to model real rigidities at the firm level but allow for full flexibility at the aggregate level. The aggregate flexibility is achieved by allowing for firm entry and exit. Our model with firm entry and exist is identical to a standard frictionless one-sector RBC model in aggregate dynamics if there is no time-to-build. In this case, aggregate technology shocks generate positive initial impulse responses for both output and inputs, which is inconsistent with the data as shown by Gali (1999) and Basu et al. (2006). However, if it takes time (say one period) for new firms to set up production plants and earn profits after entry, then our model starts to behave very differently from the standard RBC model and is able to explain the empirical facts regarding the effects of technology shocks at both sectorial and aggregate level.

3 Benchmark Model

3.1 Final Good

The economy produces only one type of final good (y). There are many identical final good producers in any period t , with each producing only a fixed quantity of the final good. Without loss of generality, this quantity is normalized to one. In a sense, each firm can be viewed as a production assembly line with fixed production capacity. There is a fixed cost, $\Phi \in (0, 1)$, to enter the final good industry. Entry and exit under perfect competition will determine the total mass (number) of final good producers, Ω_t , in each period. The intermediate good for producing y is x . Producing one unit of the final good requires a units of x , where a is a constant. Without loss of generality we can normalize both a and the price of the final good (p_y) to one, $a = p_y = 1$. Hence the production function is simply $y = x$. One can imagine the final good as pizza, which is of a particular size, and the input as flour. To produce one pizza requires a ponds of flour. Each pizza producer can choose to produce either one or zero unit of pizza, depending on the profits. The aggregate output simply equals the total number of pizza producers. Let p_x be the price of input. A final good producer's profit maximization problem is:

$$\max_x (x - p_x x) \tag{4}$$

This yields the demand for input:

$$x = \begin{cases} 1 & \text{if } p_x \leq 1 \\ 0 & \text{if } p_x > 1 \end{cases} . \tag{5}$$

Profit in each period for each producer is given by

$$\pi = \begin{cases} 1 - p_x & \text{if } p_x \leq 1 \\ 0 & \text{if } p_x > 1 \end{cases} . \tag{6}$$

In each period the aggregate supply of output (Y) is determined by the number of firms (production lines) and is equal to $\int_0^\Omega y di = \Omega y$, and the aggregate demand for input is $\int_{i=0}^\Omega x di = \Omega x$. The structure of the economy is illustrated in Figure 6.

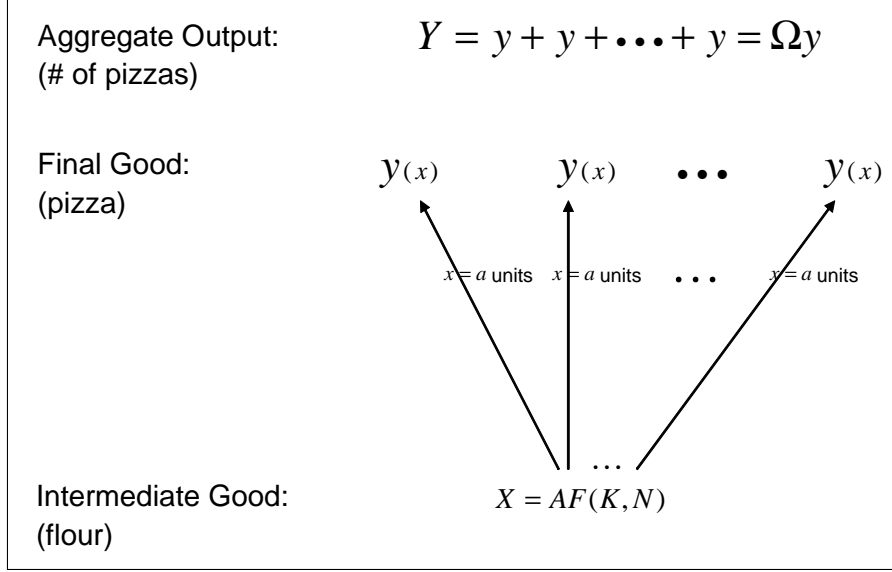


Figure 6. Production Structure.

Firm entry and exit. The setup of firm's entry and exit is similar to Ghironi and Melitz (2005). In each period, there are potentially infinite entrants, which make the final good industry perfectly competitive. The one-time fixed entry cost (Φ) is paid in terms of the final good. After entry, each firm faces a stochastic probability of exit, $\theta_t \in (0, 1)$. The probability of exit is assumed to depend on the size of aggregate technology shocks. We assume that firms must wait one period to produce output after entry due to time-to-build. The value of a firm in period t is then determined by

$$V_t = \beta E_t \Lambda_{t+1} \pi_{t+1} + E_t \sum_{j=1}^{\infty} \beta^{j+1} \left[\prod_{i=1}^j (1 - \theta_{t+i}) \right] \Lambda_{t+j+1} \pi_{t+j+1}, \quad (7)$$

where Λ_{t+j} is the ratio of marginal utilities between period $t+j$ and period t . We can also write this equation recursively as

$$V_t = \beta E_t \Lambda_{t+1} (\pi_{t+1} + (1 - \theta_{t+1}) V_{t+1}). \quad (8)$$

Free entry then implies $V_t = \Phi$. The evolution of the number of final good producers is

$$\Omega_{t+1} = (1 - \theta_t) \Omega_t + s_t, \quad (9)$$

where s is the number of new entrants in period t .¹⁰

¹⁰The fixed cost (Φ) can be interpreted, for example, as the cost of purchasing structural capital goods such as buildings or production lines. This is a corn economy with only one type of final good, which can be either

3.2 Intermediate good

In the benchmark model there is only one type of intermediate good, x . The intermediate good market is also perfectly competitive. For simplicity, we assume there are no costs to enter this market. The production function of a representative producer of the intermediate good is

$$X_t = A_t K_t^\alpha N_t^{1-\alpha}, \quad (10)$$

where A stands for total-factor-productivity (technology) shocks, and K and N stand for capital and labor. The unit cost of labor is the real wage, w , and the unit cost of renting capital from households is the sum of real interest rate and depreciation rate, $r + \delta$. Profit maximization by a representative firm gives $\alpha p_x \frac{X}{K} = r_t + \delta$ and $(1 - \alpha) p_x \frac{X}{N} = w_t$. Perfect competition implies that price equals the marginal cost, $p_x = \frac{1}{A} \left(\frac{r+\delta}{\alpha}\right)^\alpha \left(\frac{w}{1-\alpha}\right)^{1-\alpha}$. Since the intermediate good sector has only one representative firm, the aggregate supply of intermediate good is X .

3.3 Household

A representative household receives interest income by renting capital to intermediate good producers and wage income from working. It also receives net profit income (gross profits minus fixed entry costs),

$$\Pi_t = \int_{i=0}^{\Omega} \pi_t di - s_t \Phi, \quad (11)$$

from final good producers, where Ω is the number of existing incumbents and s is the number of new entrants. The household's utility maximization problem is standard:

$$\max E_0 \sum_{t=0}^{\infty} \beta^t [\log(C_t) + \gamma \log(1 - N_t)], \quad (12)$$

subject to

$$C_t + K_{t+1} = w_t N_t + (1 + r_t) K_t + \Pi_t. \quad (13)$$

The first order conditions for the household are $w_t C_t^{-1} = \gamma(1 - N_t)^{-1}$ and $C_t^{-1} = \beta E_t C_{t+1}^{-1} (1 + r_{t+1})$.

consumed or saved as investments. Thus the amount of output invested in structural capital each period depends only on the number of new firms entering the market. In this case, the probability of exit (θ) can be interpreted as the depreciation rate of the structural capital.

3.4 General equilibrium

A general equilibrium is a set of quantities and prices, $\{Y, X, K, N, \Omega, \Pi, \pi, s, p_x, w, r\}$, such that firms maximize profits, households maximize utilities, and all markets clear. The resource constraint (15) for the representative household in equilibrium becomes

$$C_t + K_{t+1} - (1 - \delta)K_t + s_t\Phi = Y_t, \quad (14)$$

where the aggregate output is determined by the number of final good producers in equilibrium, $Y_t = \Omega_t$, which in turn is also the total demand for intermediate good, $\Omega_t = X_t = A_t K_t^\alpha N_t^{1-\alpha}$. The system of equations that determine the general equilibrium thus consists of the aggregate production function, $Y_t = A_t K_t^\alpha N_t^{1-\alpha}$, the resource constraint (14), and

$$\Phi = \beta E_t \frac{C_t}{C_{t+1}} (\pi_{t+1} + (1 - \theta_{t+1})\Phi), \quad (15)$$

$$\Omega_{t+1} = (1 - \theta_t)\Omega_t + s_t, \quad (16)$$

$$\pi_t = 1 - p_{xt}, \quad (17)$$

$$\alpha p_{xt} \frac{Y_t}{K_t} = r_t + \delta, \quad (18)$$

$$(1 - \alpha) p_{xt} \frac{Y_t}{N_t} = w_t. \quad (19)$$

$$w_t C_t^{-1} = \gamma(1 - N_t)^{-1}, \quad (20)$$

$$C_t^{-1} = \beta E_t C_{t+1}^{-1} (1 + r_{t+1}). \quad (21)$$

3.5 Equivalence to standard RBC model

Suppose final good producers can start production and earn profits within the same period of entry and the probability of exit after production is one ($\theta = 1$). Then Equation (8) becomes $V = \pi$. Hence Equations (15)-(17) collapse to $\pi_t = \Phi$, $p_{xt} = 1 - \Phi$ and $s_t = \Omega_t$. The aggregate resource constraint (14) becomes

$$C_t + K_{t+1} - (1 - \delta)K_t = (1 - \Phi)A_t K_t^\alpha N_t^{1-\alpha}, \quad (22)$$

and the factor prices become $r_t + \delta = \alpha(1 - \Phi)\frac{Y_t}{K_t}$ and $w_t = (1 - \alpha)(1 - \Phi)\frac{Y_t}{N_t}$. Namely, factor prices are proportional to marginal products. Since $p_{xt} = 1 - \Phi \in (0, 1)$ is constant, Equations

(18)-(22) indicate that the dynamics of this model are the same as those implied by a standard frictionless RBC model (e.g., King, Plosser and Rebelo, 1988).

3.6 Impulse responses

Calibration. The time period is a year. Let $\beta = 0.96$, $\alpha = 0.4$, $\delta = 0.1$ and the steady-state fraction of hours worked $\bar{N} = 0.2$ (or about 35 hours per week). Let the fixed cost of entry $\Phi = 0.1$ (which implies the steady-state share of entry cost to GDP is $0.1 \times \theta$). The results are not sensitive to these parameter values. To ensure stationarity of θ_t , assume the probability of exit depends on the innovation (rather than the level) of technology shocks, $\log(\theta_t) = \eta \log(\varepsilon_t)$. The probability of exit corresponds to the business failure rate in the real world. Based on data from the U.S. (1949-1996), a one percent increase in the aggregate technology reduces the business failure rate by about 6 percent in the long run, hence we set $\eta = -6$. This negative elasticity implies that a positive aggregate technology shock reduces the probability of exit due to improved efficiency for all firms. To calibrate the steady-state value of θ , we note that the dynamics of the model variables, except the first-period response of the number of new entrants (s_t), are not sensitive to this parameter. For example, the initial responses of investment and hours are negative for any value of $\theta \in (0, 1)$. However, the initial impulse response of s_t is sensitive to this parameter: it is positive when θ is small enough but negative when θ is large enough. The average business failure rate (at annual frequency) for the U.S. economy is about 710 per 10,000 listed enterprises, implying a steady-state value close to $\bar{\theta} \approx 0.1$.¹¹ Under this value, the initial impulse response of s_t is positive. However, for larger values of $\bar{\theta}$, the model can generate negative initial response of s_t to technology shocks. The long run responses of s is always positive regardless of $\bar{\theta}$. For this reason, we simulate the model using two alternative values, $\bar{\theta} = \{0.1, 0.25\}$. These values imply a steady-state markup in the range of $1.5 \sim 3\%$, which is well within the empirical estimates suggested by the literature.

¹¹This is also the value adopted by Ghironi and Melitz (2005).

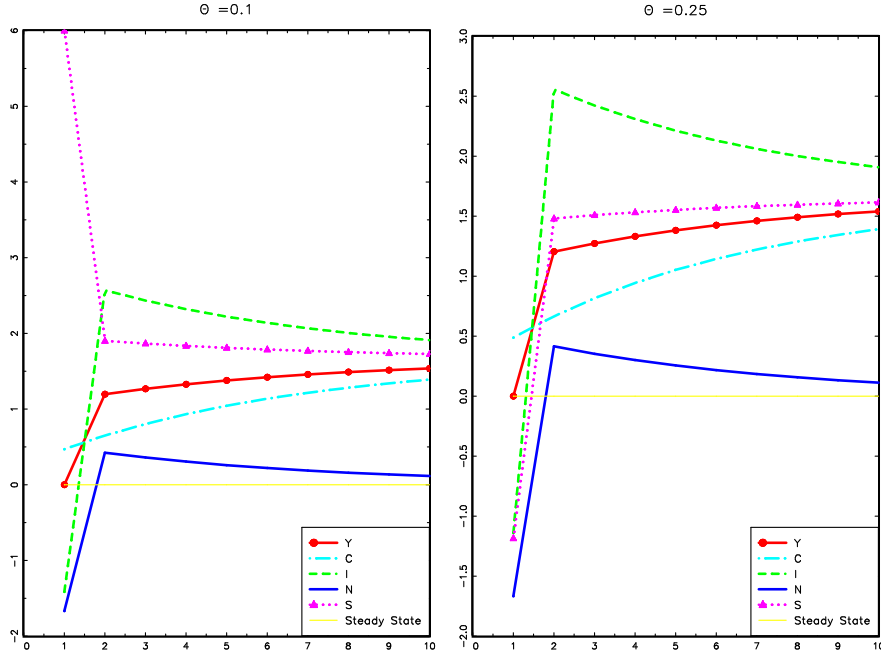


Figure 7. Impulse Responses to a Permanent Technology Shock.

Figure 7 shows that the aggregate dynamics of the benchmark model are broadly consistent with the US data. The left window in Figure 7 shows that in the initial period after a permanent increase in aggregate technology, aggregate output does not change, net business formation increases sharply, consumption rise gradually, investment and hours fall sharply. In the longer run, however, all variables increase permanently to a higher steady state. Output does not respond to technology shocks in the initial period because it is determined by the exiting number of firms when a shock hits the economy, which is a state variable determined by net business formation in the past. This short-run rigidity of output is caused by time-to-build, namely, new firms cannot produce output immediately after entry. Due to this short-run rigidity of aggregate output, demand for aggregate labor must decrease, as in a sticky price model. Consumption rises immediately after the shock because consumers correctly anticipate the increase in permanent income. Given that current income (output) is fixed, aggregate savings (investment) must fall to support the increase in consumption. Since a positive technology shock increases expected profits by reducing the marginal cost, net business formation tends to rise immediately after the shock.

The right window in Figure 7 shows that with a higher value of $\bar{\theta}$ the dynamics of net business formation change dramatically while the dynamics of the other variables remain essentially unchanged. Under a higher value of $\bar{\theta}$, net business formation may decrease in the initial period before rising to a higher steady state in the long run. This is because a higher value of $\bar{\theta}$ implies a higher probability of exit, hence a lower expected profits. Thus there is less incentive for new

firms to enter the market. Alternatively, this can be understood from a social planner’s point of view. After a positive technology shock, the planner opts to increase consumption due to a higher permanent income. Given that the current income (output) level is fixed, whether it is optimal to increase or decrease the investment in structural capital (i.e., the number of new firms) depends on the cost and the benefit. The benefit is the increased production capacity in the future, which implies higher future output. But adding new firms is also costly (the entry cost), which decreases current consumption. When $\bar{\theta}$ is large, the benefit is reduced due to a higher depreciation rate of firms. In addition, technology shocks increase the survival rate of firms in the short run ($\eta < 0$), hence mitigating the needs for investment in new firms. Consequently, the initial investment in new firms decreases. For values of $\bar{\theta}$ in between, net business formation does not respond significantly to technology shocks on impact.¹²

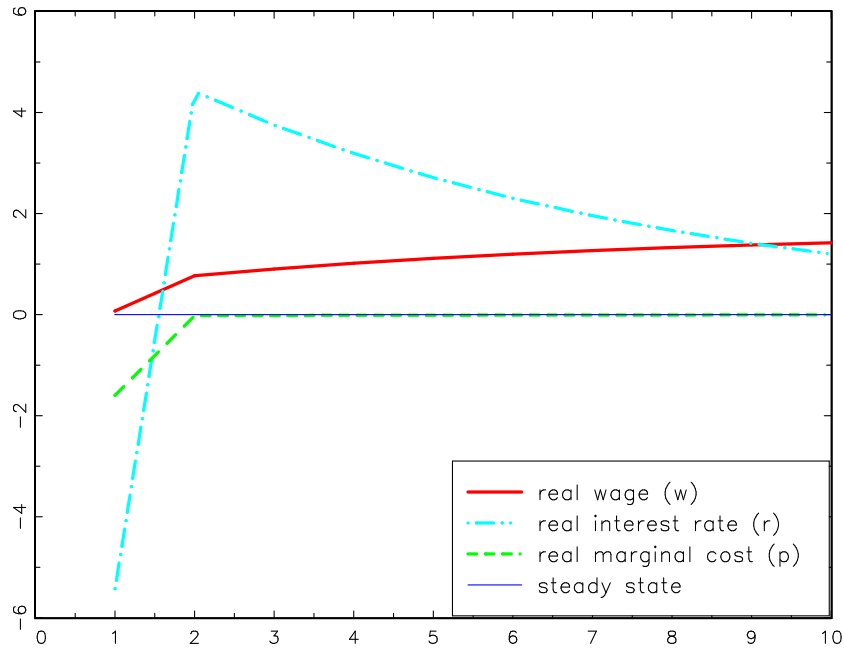


Figure 8. Impulse Responses of Factor Prices.

The impulse responses of the real wage, real interest rate and real marginal cost are graphed in Figure 8.¹³ It shows that a positive technology shock leads to a moderate increase in the real wage and a sharp decrease in the real interest rate on impact, consistent with the data. Also consistent with the data is the prediction that the real interest rate is about 10 times more

¹²The intuition that changing the value of $\bar{\theta}$ has little effect on the impulse responses of the economy except that of net business formation can be understood from the fact that s_t is a flow variable while Ω_t is a stock variable and the fact that most aggregate variables are closely related to Ω_t instead of s_t .

¹³The dynamics of factor prices are not sensitive to the value of $\bar{\theta}$.

volatile than the real wage in the intermediate run. The initial drop in the real interest rate is due to the decline in the marginal cost. Notice the highly transitory decline in marginal cost. This feature enables the real interest rate to be more volatile than the real wage in the short run because hours are more capable than capital of comoving with output over time. Entry and exit are the key to generating a time-varying marginal cost in our model.

4 Multisector Model

In order to explain the dynamic effects of technology shocks on sectorial activity, this section extends the benchmark model to a multisector economy with exactly the same type of micro-rigidity. Assume that producing one unit of the final good requires a continuum of different types of intermediate goods with measure one, $\{x_j\}_{j=0}^1$. The production function is

$$y = \int_{j=0}^1 x_j dj. \quad (23)$$

The price of x_j is denoted p_j . As in the benchmark model, the demand for x_j is rigid:

$$x_j = \begin{cases} a_j & \text{if } p_j \leq 1 \\ 0 & \text{if } p_j > 1 \end{cases}, \quad (24)$$

where a_j is a constant. Hence the vector $\langle a_j \rangle$ can be viewed as the input-output coefficients of the economy. Perhaps a good example of this final good is a computer. To produce one computer, we need a_1 units of screen, a_2 units of hard drive, a_3 units of key board, a_4 units of chips, and so on. The gross profit function for a final good producer is $\pi = y - \int_0^1 a_j p_j dj$.

Except for expanding the input type from one to many, the structure of the model is similar to the one-sector benchmark model. For example, the value of the firm is still $V_t = \beta E_t \Lambda_{t+1} (\pi_{t+1} + (1 - \theta_{t+1})V_{t+1})$ and the law of motion for the number of final good firms is still $\Omega_{t+1} = (1 - \theta_t)\Omega_t + s_t$. As before, each firm in the final good sector can produce only a fixed number of computers. Without loss of generality, this number is also normalized to one as in the benchmark model, $y = \int_{j=0}^1 a_j dj = 1$. As before, the production capacity of each firm is fixed. Hence, in order to produce more computers, there is the need of more firms. Thus the aggregate supply of computers is still determined by the number of firms: $Y_t = \int_{i=0}^{\Omega_t} y di = \Omega_t$.

The production functions for intermediate goods are similar across sectors:

$$X_j = AZ_j F(K_j, N_j), \quad (25)$$

where Z_j represents sector-specific technology shock process orthogonal to other sectorial technology shocks Z_i ($i \neq j$) and the aggregate technology shock process A . The structure of the economy is illustrated in Figure 9.

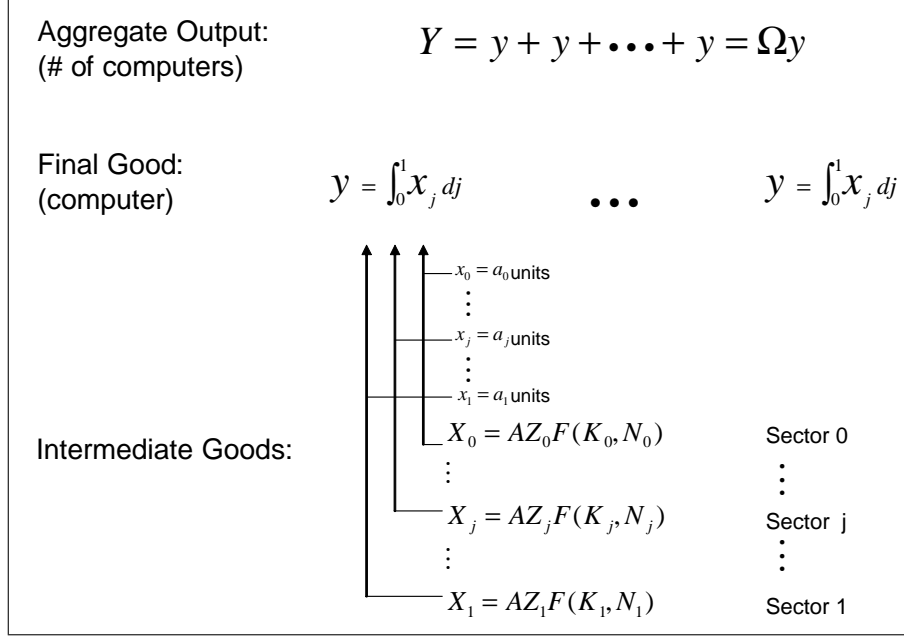


Figure 9. Multi-Sector Model.

As in the benchmark model, a representative household receives interest payments by renting capital to intermediate producers and wages from working. It also receives net profit income ($\Pi = \int_{i=0}^{\Omega} \pi di - s\Phi$) from all final good producers, where Ω is the number of existing incumbent firms and s is the number of new entrants. The household's utility function is identical to the benchmark model and the budget constraint is given by $C_t + K_{t+1} = w_t N_t + (1 + r_t)K_t + \Pi_t$, where $K = \int_0^1 K_j dj$ and $N = \int_0^1 N_j dj$. The first order conditions for the household are the same as before. Notice the first order conditions are identical across j .

Profit maximization for each intermediate-good firm in sector j gives the following first order conditions, $\alpha p_j \frac{X_j}{K_j} = r + \delta$ and $(1 - \alpha) p_j \frac{X_j}{N_j} = w$. Combining with the production function gives the marginal cost of good j :

$$p_j = \frac{1}{AZ_j} \left(\frac{r + \delta}{\alpha} \right)^\alpha \left(\frac{w}{1 - \alpha} \right)^{1-\alpha}. \quad (26)$$

The aggregate output can also be expressed as

$$Y = \int_{i=0}^{\Omega} \left(\int_{j=0}^1 a_j dj \right) di = \int_{j=0}^1 (a_j \Omega) dj, \quad (27)$$

where $a_j \Omega$ is the aggregate demand for intermediate good j . The aggregate supply of intermediate good j is X_j . Hence the ratio between any two types of intermediate goods is constant,

$$\frac{X_j}{X_i} = \frac{a_j}{a_i}. \text{ The first order conditions for labor and capital then imply } \frac{Z_j K_j}{a_j} = \frac{Z_i K_i}{a_i} \text{ and } \frac{Z_j N_j}{a_j} = \frac{Z_i N_i}{a_i}.$$

Re-arranging and integrating over i on both sides of the equations gives $K_j = \left(\int_0^1 \frac{a_i}{Z_i} di \right) \frac{a_j}{Z_j} K$ and $N_j = \left(\int_0^1 \frac{a_i}{Z_i} di \right) \frac{a_j}{Z_j} N$. Note that the aggregator $\left(\int_0^1 \frac{a_i}{Z_i} di \right)$ is independent of Z_j for all j , given the orthogonality assumption among sectorial shocks. The distribution of Z_j can be chosen such that the normalization, $\left(\int_0^1 \frac{a_i}{Z_i} di \right) = 1$, holds. Thus we have

$$K_j = \frac{a_j}{Z_j} K, \quad (28)$$

$$N_j = \frac{a_j}{Z_j} N. \quad (29)$$

Substituting K_j and N_j into the sectorial production function, $X_j = AZ_j K_j^\alpha N_j^{1-\alpha}$, gives

$$X_j = a_j A K^\alpha N^{1-\alpha}. \quad (30)$$

In equilibrium the final good production function becomes¹⁴

$$Y = \int_{j=0}^1 (a_j \Omega) dj = \int_{j=0}^1 X_j dj = A K^\alpha N^{1-\alpha}. \quad (31)$$

4.1 Impulse responses

Impulse responses of aggregate variables, such as output, consumption, investment and hours, to aggregate technology shocks are exactly the same as in the benchmark one-sector model. Impulse responses of sectorial output and inputs to both aggregate and sector-specific technology shocks can be inferred from Equations (28)-(30). First, sectorial output (X_j) and inputs (K_j, N_j) are proportional to aggregate output (Y) and aggregate inputs (K, N), respectively.

¹⁴Alternatively, we can derive the aggregate final good production function from the market clearing condition, $a_j \Omega = X_j$ for all j . This implies $\Omega (= Y) = \frac{X_j}{a_j} = A K^\alpha N^{1-\alpha}$.

Hence the impulse responses of sectorial output and sectorial inputs behave similarly to aggregate output and inputs, respectively, under aggregate technology shocks. This is consistent with the data. Second, sectorial technology Z_j affects only sectorial inputs but not sectorial output. Hence, under sector-specific technology shocks, sectorial output remains constant but sectorial inputs decrease when Z_j increases, as in the data. Notice that the results do not depend on the elasticity of substitution across intermediate goods, σ .

4.2 Equivalence to standard RBC model

Denote $P = \frac{1}{A} \left(\frac{r+\delta}{\alpha} \right)^\alpha \left(\frac{w}{1-\alpha} \right)^{1-\alpha}$. The gross profit of each final good producer is then $\pi = 1 - \int_0^1 a_j p_j dj = 1 - P$. Utilize the expressions for X_j, K_j and N_j , we can show that the market prices for capital and labor can be written as $r + \delta = \alpha P \frac{Y}{K}$ and $w = (1 - \alpha) P \frac{Y}{N}$. Given that there are s_t number of new entrants in period t , the aggregate net profits from all final good producers are then $Y(1 - P) - s_t \Phi$. The household's resource constraint becomes identical to (14), $C_t + K_{t+1} - (1 - \delta)K_t + s_t \Phi = Y_t$.

Suppose firms can start production immediately upon entry and $\theta = 1$. These assumptions imply $P = 1 - \Phi$ and $\Omega_t (= Y_t) = s_t$. The aggregate resource constraint then becomes identical to (22), $C_t + K_{t+1} - (1 - \delta)K_t = (1 - \Phi)Y_t$. Clearly, the dynamics of aggregate output, consumption, investment and hours under aggregate technology shocks in this model are now equivalent to a standard frictionless one-sector RBC model.

5 Explaining Heterogeneity

Although our model is broadly consistent with the stylized facts reported in Section 2, it lacks the ability to explain the heterogeneous responses across sectors. Namely, after a positive sector-specific technology shock, factor demand decreases only on average, but in some sectors the factor demand increases (see, e.g., Figure 5). In this section, we show that the model can be easily extended to account for this heterogeneity of dynamic responses of sectorial activity to technology shocks.

As before, assume that producing a final good requires a continuum of different types of intermediate goods, $\{x_j\}_{j=0}^1$. However, the input-output coefficient in Equation (24), a_j , is now re-interpreted as the productivity of one unit of intermediate good j in producing the final good. Under this interpretation, a_j can be considered as a random draw from a distribution

$f_j(a)$ in sector j . Hence, the production function of a final good firm (i) can be rewritten as

$$y_i = \int_0^1 a(i, j) I(i, j) dj, \quad (32)$$

where the index function $I(i, j)$ reflects the rigidity in factor demand: $I(i, j) = 1$ if $a(i, j) \geq p_j$ and $I(i, j) = 0$ if $a(i, j) < p_j$. Namely, each final good firm in each period draws an idiosyncratic random productivity for each type of intermediate good, so that firm i can transform one unit of intermediate good j into $a(i, j)$ units of final good with probability $f_j(a)$. Notice that we assume the distribution function differs across sector j : $f_j(a) \neq f_k(a)$ if $j \neq k$. Denote $F_j(p_j) = 1 - \int_{a \geq p_j} a(i, j) f_j(a) da$ as the probability that $a(i, j) < p_j$. Since the demand for each type of intermediate good is either zero or one, the aggregate demand for intermediate good j , by the law of large number, is then given by

$$X_j = \int_0^\Omega I(i, j) di = [1 - F_j(p_j)] \Omega. \quad (33)$$

The negative of the price elasticity of demand for X_j is determined by

$$\epsilon_j = \frac{p_j f_j(p_j)}{1 - F_j(p_j)} > 0. \quad (34)$$

Impulse responses to sector-specific technology shocks. As before, the demand functions for labor and capital by each firm in the intermediate good producing sector j are determined, respectively, by the first order conditions, $\alpha p_j X_j = (r + \delta) K_j$ and $(1 - \alpha) p_j X_j = w N_j$. The price of intermediate good j is still given by $p_j = \frac{1}{AZ_j} \left(\frac{r+\delta}{\alpha}\right)^\alpha \left(\frac{w}{1-\alpha}\right)^{1-\alpha}$. Since sector-specific technology shocks (Z_j) do not affect the real wage and the real interest rate, around the steady state the percentage change of factor demand for capital and labor with respect to Z_j are given, respectively, by

$$\hat{K}_j = (\epsilon_j - 1) \hat{Z}_j, \quad (35)$$

$$\hat{N}_j = (\epsilon_j - 1) \hat{Z}_j; \quad (36)$$

where circumflex denotes log-linearization around the steady state. Clearly, under a sector-specific technology shock, demand for capital and labor will decrease in sector j if $\epsilon_j < 1$, and will increase in sector j if $\epsilon_j > 1$. In particular, the changes are permanent if the shocks

are permanent. These predictions are consistent with the stylized facts presented in Figure 5. Notice that the model collapse to the previous one if $\epsilon_j = 0$ for all j . The average impulse response across sectors is determined by $E\epsilon_j - 1 = \int_0^1 \epsilon_j - 1$. The data suggests that $E\epsilon_j < 1$, which is the assumption we make.

Hence, allowing for heterogeneity in the distribution of $a(i, j)$ can explain the heterogenous responses of inputs across sectors. The question is: will this affect the pattern of impulse responses of the model to aggregate technology shocks? This question is addressed below.

Impulse responses to aggregate technology shocks. Using Equation (33), the ratio between any two types of intermediate good demand is $\frac{X_j}{X_i} = \frac{1-F_j}{1-F_i}$. The first order conditions for capital and labor then imply $\frac{Z_j K_j}{1-F_j} = \frac{Z_i K_i}{1-F_i}$ and $\frac{Z_j N_j}{1-F_j} = \frac{Z_i N_i}{1-F_i}$. Rearranging and integrating over $i \in [0, 1]$ on both sides of the two identities gives the relationships, $K_j = \left(\int_0^1 \frac{1-F_i}{Z_i} di \right)^{-1} \frac{1-F_j}{Z_j} K$ and $N_j = \left(\int_0^1 \frac{1-F_i}{Z_i} di \right)^{-1} \frac{1-F_j}{Z_j} N$. In the absence of sector-specific technology shocks ($Z_j = 1$ for all j), we have $p_j = p$ for all j and

$$K_j = v(1 - F_j)K, \quad (37)$$

$$N_j = v(1 - F_j)N; \quad (38)$$

where $v \equiv \left(\int_0^1 (1 - F_j) dj \right)^{-1}$. Substituting these relationships into the sectorial production function (with $Z_j = 1$), $X_j = AK_j^\alpha N_j^{1-\alpha}$, gives

$$X_j = v(1 - F_j)AK^\alpha N^{1-\alpha}. \quad (39)$$

Comparing with Equation (33) gives the equilibrium number of firms,

$$\Omega = vAK^\alpha N^{1-\alpha}. \quad (40)$$

The factor demand functions for capital and labor can also be rewritten as

$$\alpha p \frac{AK^\alpha N^{1-\alpha}}{K} = r + \delta, \quad (41)$$

$$(1 - \alpha) p \frac{AK^\alpha N^{1-\alpha}}{N} = w. \quad (42)$$

Clearly, the aggregate dynamics of factor prices are similar to those in the previous section.

By changing the order of integration and by the law of large number, the aggregate output is given by

$$Y = \Omega \int_0^1 G_j(p) dj,$$

where $G_j(p) \equiv \int_{a \geq p} a f_j(a) da$ is the expected (average) marginal product of intermediate good j and $\int G_j dj$ is the average final output per firm. Similarly, the gross profit for the final good sector is

$$\begin{aligned} \Pi &= \int_0^\Omega \left(\int_0^1 (a(i, j) - p) I(i, j) dj \right) di \\ &= \Omega \int_0^1 [G_j - p(1 - F_j)] dj. \end{aligned} \quad (43)$$

Hence the average (expected) profit of a final good firm is determined by

$$\pi = \int_0^1 [G_j - p(1 - F_j)] dj. \quad (44)$$

The value of a firm is given by $V_t = \beta E_t \frac{\lambda_{t+1}}{\lambda_t} (\pi_{t+1} + (1 - \theta_{t+1}) V_{t+1})$. Free entry implies $V_t = \Phi$. The household's problem is the same as before (see the Appendix for details of log-linearizing the model and parameter calibration).

Figure 10 shows that, for the average price elasticity of demand less than one (e.g., $\int_0^1 \epsilon_j dj = 0.2$), the impulse responses of aggregate variables to an aggregate technology shock mimic those of the previous model discussed in Section 4, with the exception that the initial response of output is not exactly zero but positive.¹⁵ The model is able to explain several key stylized facts of the business cycle emphasized by Kydland and Prescott (1982): (i) Aggregate consumption, investment and hours comove with output; and (ii) Aggregate consumption is less volatile while aggregate investment is more volatile than output. For example, in terms of annual growth rate, the ratio of standard deviation between consumption and output is 0.61 in the model and 0.62 in the data, and that for investment is 3.2 in the model and 3.1 in the data. The match

¹⁵Since aggregate output is determined by $Y = \Omega \int G_j dj$, even if the number of firms (Ω) does not change initially, technology shocks can affect aggregate output via changing individual firms' expected payoff $\int_{a \geq p} a f(a) da$ when the marginal cost (p) changes. The effect is larger the larger the price elasticity of firms' demand. Hence, when the average price elasticity of demand approaches infinity, the model starts to behave like a standard RBC model; namely, labor, investment and the real interest rate increase sharply on impact. Notice that an infinitely large price elasticity of demand implies that prices are very sticky relative to demand. Hence the implication of our model is the opposite of the sticky price model.

could not be better. The correlations of consumption, investment and hours to output are 0.55, 0.88 and 0.61, respectively, in the model, and 0.75, 0.80 and 0.42 for their counter parts in the U.S. economy. The match is quite good although not perfect. This brings us back to the first point raised in the beginning of the paper regarding the importance of technology shocks in explaining the business cycle; namely, the fact that investment and hours fall sharply on impact under technology shocks does not logically imply that they are countercyclical with respect to output. Things also depend on whether their forecastable future movements (in the terminology of Rotemberg and Woodford, 1996) move together with that of output. Figure 10 shows that investment and hours are expected to move with output in the future beyond the impact period despite that they have the opposite signs of initial responses to output. Hence, investment growth and hours growth are procyclical with respect to output growth, as in the data.

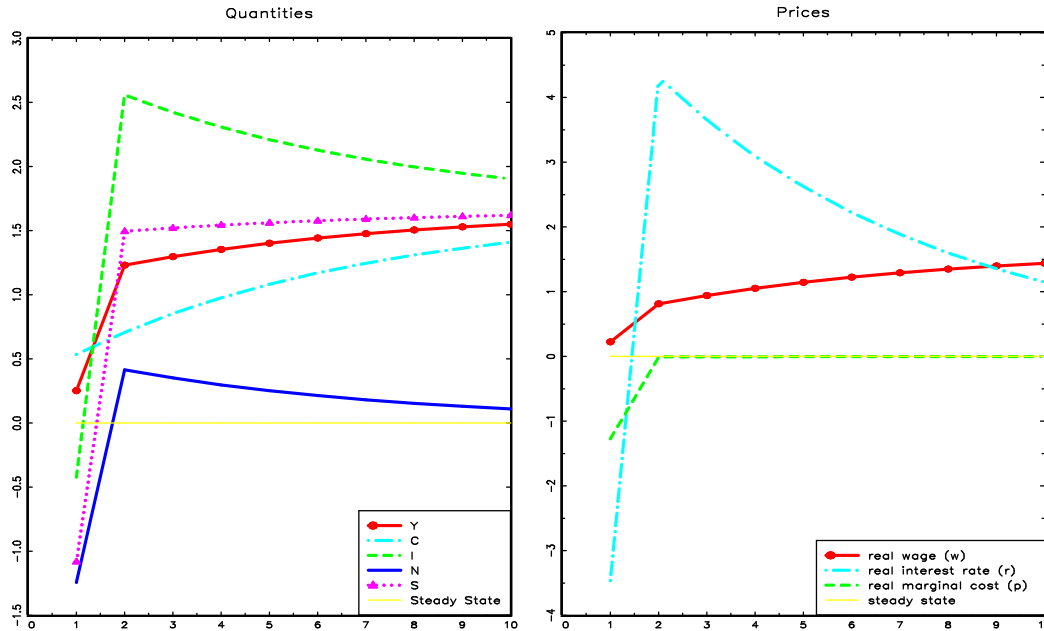


Figure 10. Impulse Responses to an Aggregate Technology Shock.

6 Discussion

A micro level rigidity in factor-demand does not by itself imply any aggregate rigidities, as long as the number of firms can respond to aggregate shocks on impact. Hence the aggregate dynamics of our model are identical to those of a frictionless RBC model when there is no time-to-build. To further illustrate the usefulness and macroeconomic implications of our model, this section shows that many familiar aggregate production functions with constant returns to

scale and positive elasticity of substitution across aggregate inputs can be derived as special cases from our model with firm entry and exit, despite the factor-demand rigidities at the firm level.

Consider the production function in (32), $y_i = \int_0^1 a(i, j)I(i, j)dj$. Assume that $a(i, j)$ follows the Pareto distribution $F(a) = 1 - \left(\frac{a_{\min}}{a}\right)^\sigma$ for all j with the location parameter $a_{\min} > 0$, the shape parameter $\sigma > 0$ and the support $a \in [a_{\min}, \infty)$. Without loss of generality, assume $a_{\min} = 1$. Hence $F(a) = 1 - \left(\frac{1}{a}\right)^\sigma$. It follows immediately that the aggregate demand for intermediate good j is given by

$$X_j = \left(\frac{1}{p_j}\right)^\sigma \Omega, \quad (45)$$

which has a constant price elasticity of σ . The aggregate output in this economy is given by $Y = \int_0^\Omega \left(\int_0^1 a(i, j)I(i, j)dj\right) di$. By changing the order of integration and by the law of large number, we have $Y = \Omega \int_0^1 G_j dj$, where $G_j \equiv \int_{a_{i,j} \geq p_j} a(i, j)f(a)da$ is the expected output of using intermediate good j for each firm. Under the Pareto distribution, we have $G_j = \frac{\sigma}{\sigma-1} \left(\frac{1}{p_j}\right)^{\sigma-1}$. Hence the aggregate output is

$$Y = \frac{\sigma}{\sigma-1} \Omega \int_0^1 \left(\frac{1}{p_j}\right)^{\sigma-1} dj = \frac{\sigma}{\sigma-1} \Omega^{\frac{1}{\sigma}} \int X_j^{\frac{\sigma-1}{\sigma}} dj, \quad (46)$$

where the second equality is obtained under (45). If $\sigma > 1$, then Y is well defined.

The expected profit of a final good firm is given by

$$\pi = \int_0^1 [G_j - p_j(1 - F(p_j))] dj = \frac{1}{\sigma-1} \int_0^1 \left(\frac{1}{p_j}\right)^{\sigma-1} dj = \frac{Y}{\sigma\Omega}. \quad (47)$$

Assuming no time-to-build and the probability of exist after production is one ($\theta = 1$), free entry then implies $\pi = \Phi$. Hence we have $\Omega = \frac{Y}{\sigma\Phi}$. Substituting this into the aggregate output in (46) and re-arranging gives the Dixit-Stiglitz CES aggregate production function,

$$Y = A(\Phi) \left(\int_0^1 X_j^{\frac{\sigma-1}{\sigma}} dj\right)^{\frac{\sigma}{\sigma-1}}, \quad (48)$$

where $A(\Phi) \equiv \left(\frac{\sigma}{\sigma-1}\right)^{\frac{\sigma}{\sigma-1}} \left(\frac{1}{\sigma\Phi}\right)^{\frac{1}{\sigma-1}}$. Notice that there is an additional constant, A , in front of the production function. This constant is a function of the parameter σ and depends negatively

on the fixed cost (Φ), demonstrating that the conventional measure of total factor productivity (TFP) can depend on market structures of the economy. In particular, trade policies affecting the cost of entering a market can affect TFP. This result shares the same spirit with Lagos (2006).

A special case of the above example is when the production function of the final good firm is given by

$$y_i = a_i k + b_i n, \quad (49)$$

where k is capital, n is labor, and $\{a_i, b_i\}$ are independent random draws from a common distribution. The factor demand for capital and labor are given, respectively, by

$$k = \alpha \text{ if } a_i \geq r, \text{ otherwise } k = 0; \quad (50)$$

$$n = \beta \text{ if } b_i \geq w, \text{ otherwise } n = 0; \quad (51)$$

where $\{r, w\}$ stand for prices of capital and labor, respectively. The output of a particular firm is then

$$y_i = \alpha a_i I(a_i) + \beta b_i I(b_i), \quad (52)$$

where $I(a_i)$ and $I(b_i)$ are index functions. The expected profit of a final good firm i is determined by

$$\pi_i = \alpha \int_r^\infty (a - r) f(a) da + \beta \int_w^\infty (b - w) f(b) db. \quad (53)$$

With the Pareto distribution, it follows immediately that the aggregate demand for capital and labor are determined, respectively, by

$$K = \alpha \Omega \left(\frac{1}{r} \right)^\sigma, \quad (54)$$

$$L = \beta \Omega \left(\frac{1}{w} \right)^\sigma. \quad (55)$$

The aggregate output is then given by

$$\begin{aligned} Y &= \left[\alpha \int_r^\infty a f(a) da + \beta \int_w^\infty a f(a) da \right] \Omega \\ &= \frac{\sigma}{\sigma - 1} \left[\alpha \left(\frac{1}{r} \right)^{\sigma-1} + \beta \left(\frac{1}{w} \right)^{\sigma-1} \right] \Omega. \end{aligned} \quad (56)$$

Since the expected profit is $\pi = \frac{1}{\sigma-1} \left[\alpha \left(\frac{1}{r}\right)^{\sigma-1} + \beta \left(\frac{1}{w}\right)^{\sigma-1} \right] = \Phi$, this implies $Y = \sigma\Phi\Omega$. Combining with the aggregate factor demand functions (54) and (55), we obtain the standard text-book aggregate CES production function,

$$Y = A(\Phi) \left(\alpha^{\frac{1}{\sigma}} K^{\frac{\sigma-1}{\sigma}} + \beta^{\frac{1}{\sigma}} L^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}, \quad (57)$$

where $A(\Phi)$ is the same as before.

It is also possible to deduce a familiar quadratic aggregate production function from our model if the Pareto distribution function is replaced by the uniform distribution function. Consider $y_i = \int_0^1 a(i, j) I(i, j) dj$, where a is a random draw from the uniform distribution function with support $[0, 1]$. The aggregate demand for intermediate good j is

$$X_j = \begin{cases} (1 - p_j)\Omega, & \text{if } p_j \in [0, 1) \\ 0, & \text{if } p_j \geq 1 \end{cases}. \quad (58)$$

The aggregate output is determined by $Y = \frac{\Omega}{2} \int_0^1 (1 - p_j^2) dj$. Substituting out p_j using the aggregate demand function (58), $p_j = 1 - \frac{X_j}{\Omega}$, we have

$$Y = \int_0^1 X_j dj - \frac{1}{2\Omega} \int_0^1 X_j^2 dj. \quad (59)$$

The profit function is

$$\pi_t = \int_0^1 [G_j - p_j(1 - F_j)] dj = \frac{1}{2} \int_0^1 (1 - p_j)^2 dj. \quad (60)$$

With free entry, we have $\pi_t = \Phi$. Combining (60) with the aggregate demand function (58) gives $\Omega = \left(\frac{1}{2\Phi} \int X_j^2 dj \right)^{\frac{1}{2}}$. Substituting this into (59) gives the quadratic aggregate production function,

$$Y = \int_0^1 X_j dj - \left(\frac{\Phi}{2} \right)^{\frac{1}{2}} \left(\int_0^1 X_j^2 dj \right)^{\frac{1}{2}}. \quad (61)$$

7 Conclusion

In this paper we have proposed a flexible price RBC model with entry and exit to explain the puzzling effects of technology shocks on the economy, especially the asymmetric impacts

of aggregate and sector-specific technology shocks on sectorial activity. Key elements of our explanation are net business formation at the aggregate level and factor-demand rigidity at the micro-level. Our model collapses to a standard frictionless one-sector RBC model if there is no time-to-build upon firms' entry.¹⁶ Hence time-to-build is the only important feature differentiating our model from a standard one-sector RBC model in aggregate dynamics. We view our approach as an alternative to the sticky price approach advocated by Gali (1999) and Basu et al. (2006). An additional contribution of our paper is that it provides a micro foundation for standard aggregate production functions and TFP. Our analysis rejects the premature conclusion that the technology-driven flexible-price RBC hypothesis is dead.

8 Appendix

In equilibrium, the system of equations are summarized by

$$\Omega_t \int_0^1 (1 - F_{jt}) dj = A_t K_t^\alpha N_t^{1-\alpha} \quad (\text{A1})$$

$$Y_t = \Omega_t \int_0^1 G_{jt} dj \quad (\text{A2})$$

$$\pi_t = \int_0^1 G_{jt} dj - p_t \int_0^1 (1 - F_{jt}) dj \quad (\text{A3})$$

$$\Phi = \beta E_t \frac{C_t}{C_{t+1}} (\pi_{t+1} + (1 - \theta_{t+1}) \Phi) \quad (\text{A4})$$

$$\Omega_{t+1} = (1 - \theta_t) \Omega_t + s_t \quad (\text{A5})$$

$$\alpha p_t A_t K_t^{\alpha-1} N_t^{1-\alpha} = r_t + \delta \quad (\text{A6})$$

$$(1 - \alpha) p_t A_t K_t^\alpha N_t^{-\alpha} = w_t \quad (\text{A7})$$

$$w_t C_t^{-1} = \gamma (1 - N_t)^{-1} \quad (\text{A8})$$

$$C_t^{-1} = \beta E_t C_{t+1}^{-1} (1 + r_{t+1}) \quad (\text{A9})$$

$$C_t + K_{t+1} - (1 - \delta) K_t + s_t \Phi = Y_t. \quad (\text{A10})$$

Notice that only the first three equations are different from the previous model in Section (4).

¹⁶The equivalence also requires $\theta = 1$, namely, firms can survive for only one period after entry and need to re-enter the market in each period. But this assumption is not crucial. The dynamics of the model are not sensitive to the value of θ .

Define $\mu_j \equiv \frac{p(1-F_j)}{G_j}$. Notice that the numerator is the expected cost and the denominator is the expected output of using intermediate good j , hence μ_j can be interpreted as the expected marginal cost of intermediate good j . Since $G_j = \int_p^\infty a f_j(a) da > p \int_p^\infty f_j(a) da = p(1-F_j)$, we have $\mu_j < 1$ and $\mu_j \epsilon_j < \epsilon_j$ for all j . This implies $\int \mu_j \epsilon_j dj < \int \epsilon_j dj$. The price elasticity of G_j is given by $-\frac{p^2 f_j}{G_j} = -\frac{p(1-F_j)}{G_j} \frac{p f_j}{1-F_j} = -\mu_j \epsilon_j$.

Calibration. For simplicity, we assume that in the steady state, $F_j(p)$ and $G_j(p)$ are the same across intermediate goods sector j , but the probability density function $f_j(p)$ remains heterogeneous across j . This is enough to ensure that the sectorial impulse responses to technology shocks remain heterogeneous across sectors. Using circumflex to denote a log-linearized variable around its steady state and using $\bar{\epsilon}$ to denote $\int \epsilon_j dj$, log-linearizing the first three equations gives

$$\alpha \hat{K}_t + (1 - \alpha) \hat{N}_t + \hat{A}_t + \bar{\epsilon} \hat{p}_t = \hat{\Omega}_t \quad (\text{A11})$$

$$\hat{Y}_t = \hat{\Omega}_t - \mu \bar{\epsilon} \hat{p}_t \quad (\text{A12})$$

$$\hat{\pi}_t = \frac{\int G_j dj}{\pi} (-\mu \bar{\epsilon}) \hat{p}_t + \frac{\pi - \int G_j dj}{\pi} (1 - \bar{\epsilon}) \hat{p}_t. \quad (\text{A13})$$

Note $\int G_j dj = \frac{Y}{\Omega}$. By Equation (A4), we have $\pi = [\beta^{-1} - (1 - \theta)]\Phi$ in the steady state. The total fixed cost is $\theta\Omega\Phi$ and supposing it accounts for the fraction $\xi \equiv \frac{\theta\Omega\Phi}{Y}$ of final output, then we have $(\int G_j dj)/\pi = \frac{Y}{\Omega\pi} = \frac{\theta\Phi}{\pi\xi} = \frac{\beta\theta}{1-\beta(1-\theta)} \frac{1}{\xi}$. So equation (A13) can be rewritten as

$$\hat{\pi}_t = -\frac{\beta\theta}{1-\beta(1-\theta)} \frac{1}{\xi} \mu \bar{\epsilon} \hat{p}_t - \left(\frac{\beta\theta}{1-\beta(1-\theta)} \frac{1}{\xi} - 1 \right) (1 - \bar{\epsilon}) \hat{p}_t. \quad (\text{A14})$$

In addition, if we assume without loss of generality that the expected marginal cost equals the equilibrium price of intermediate good in the steady state, $\mu_j = p$, then $G_j = 1 - F_j$ and by Equations (A1)-(A3) we have $Y = AK^\alpha N^{1-\alpha}$ and $\pi = (1 - \mu) \frac{Y}{\Omega}$. In this case, the steady-state marginal cost is determined by $\mu = 1 - \frac{\pi\Omega}{Y} = 1 - \frac{\xi(1-\beta(1-\theta))}{\beta\theta}$ and the dynamics of firm's profit can be further simplified to

$$\hat{\pi}_t = -\frac{\mu}{1 - \mu} \hat{p}_t. \quad (\text{A15})$$

Consequently, the heterogeneous-firm model has just two additional parameters to calibrate, namely, the steady-state share of entry cost to GDP (ξ) and the average price elasticity across sectors ($\bar{\epsilon}$). Let $\xi = 0.01$, $\bar{\epsilon} = 0.2$, and the other parameters remain the same as in the previous

model, namely, $\beta = 0.96$, $\delta = 0.1$, $\alpha = 0.4$, $\theta = 0.25$ and the steady state hours worked $\bar{N} = 0.2$. These parameter values imply the steady-state markup is about one percent.¹⁷

¹⁷Assuming larger markups does not affect our results.

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