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Adjustment: A New Keynesian Perspective**

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FRANCESCO FURLANETTO,
TOMMY SVEEN AND
LUTZ WEINKE



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Technology and the Two Margins of Labor Adjustment: A New Keynesian Perspective*

Francesco Furlanetto^a, Tommy Sveen^b, Lutz Weinke^c

Norges Bank^a

BI Norwegian Business School^b

Humboldt-Universität zu Berlin^c

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Abstract

Canova et al. (2010 and 2012) estimate the dynamic response of labor market variables to technological shocks. They show that investment-specific shocks imply almost exclusively an adjustment along the intensive margin (i.e., hours worked), whereas for neutral shocks the largest share of the adjustment takes place along the extensive margin (i.e., employment). In this paper we develop a New Keynesian model featuring capital accumulation, two margins of labor adjustment and a hiring cost. The model is used to analyze a novel economic mechanism to explain that evidence.

Keywords: Technological Shocks, Sticky Prices, Labor Market.

JEL Classification: E22, E24, E32

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1 Introduction

The effect of neutral technology shocks on hours worked has received much attention in macroeconomics. For instance, the seminal paper by Galí (1999) estimates a negative response of hours after a positive shock to total factor productivity by means of a structural vector autoregressive (SVAR) model identified through a long-run restriction. The latter can be justified in a large class of business cycle models (including both Real Business Cycle (RBC) and New Keynesian (NK) models). That empirical result questions the relevance of technology shocks as the main driving force of aggregate fluctuations, for in the data hours worked is pro-cyclical. Nominal rigidities (in the form of sticky prices and/or sticky wages as in Galí 1999) or real rigidities (in the form of habit persistence and capital adjustment costs as in Francis and Ramey 2005) can explain that empirical evidence in the context of modern DSGE models.¹

Canova et al. (2010 and 2012) have refined the empirical evidence on the propagation of technological shocks on labor market variables by allowing adjustment along both the intensive margin (i.e., hours worked) and the extensive margin (i.e., employment). Using an SVAR model identified through long-run restrictions as in Fisher (2006), they arrive at the following estimation result. Labor input contracts along both margins in the aftermath of a positive neutral technology shock, and the largest share of that adjustment takes place along the extensive margin. They also investigate the effects of investment-specific technology shocks and find that they have an expansionary effect on total hours. In this case, however, the corresponding adjustment results predominantly from changes along the intensive margin.

The present paper shows that the empirical evidence described above can be explained within a New Keynesian set-up with labor market frictions. In fact, the proposed model has only two additional features with respect to the standard textbook New Keynesian model: capital accumulation, since we are interested in analyzing

¹For an overview of that literature, see Galí and Rabanal (2005).

dynamic consequences of investment-specific shocks, and labor market frictions with two margins of adjustment, since we want to study the split across the two margins. Our theoretical explanation for the relative importance of the two margins of labor adjustment in response to the two alternative forms of technological shocks is novel and surprisingly simple. Employment relationships are costly to establish in our model. The extensive margin of labor adjustment to an economic shock is therefore quantitatively important, if the shock makes a long-term investment worthwhile. But this is the case for a persistent shock to total factor productivity. On the other hand, an expansionary investment-specific technology shock incentivizes firms to use the more flexible hours margin to adjust to the shock. The reason is that firms can only take advantage of this shock by investing. But additional investment demand in the economy creates a short-run extra need for labor input, which makes it optimal for firms to use predominantly the more flexible hours margin in their adjustment to the shock.

Let us relate our results to those in the literature. Sveen and Weinke (2009) have analyzed the role of labor adjustment at both the intensive and the extensive margin for inflation dynamics in the aftermath of monetary policy shocks. In the present paper we extend that framework to make it suitable for an analysis of our new research questions. As explained in the previous paragraph, those questions regard the dynamic consequences of technological shocks. Our results point at an interesting alternative to the theoretical mechanism proposed by Michelacci and Lopez-Salido (2007). Those authors have developed a business cycle model with labor market frictions, in the context of which neutral technological progress prompts waves of Schumpeterian creative destruction. Their analysis offers an interesting theoretical explanation of the empirical evidence on the propagation of technological shocks on labor market variables. Compared with their work our explanation combines, however, features which are standard in the DSGE models which are nowadays routinely used by researchers inside and outside the academic world to analyze a wide range of issues related to business cycle fluctuations. Another strand of the recent

literature integrates labor market frictions into fully-fledged medium-scale DSGE models that are suitable for model estimation (see, e.g., Christiano et al. 2016). Our focus is more specific. We use a relatively simple model to illustrate how a small set of assumptions that are standard in the DSGE literature helps explain the dynamic consequences of alternative technological shocks for labor market variables of interest. Our paper therefore conducts a positive analysis and this differentiates it from the recent contributions with a normative focus (see, e.g., Galí 2011).

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 discusses our results and section 4 concludes.

2 The Model

Our New Keynesian model features labor market frictions and two margins of labor adjustment as in Sveen and Weinke (2009). In addition, we allow for endogenous capital accumulation subject to a convex capital adjustment cost. In what follows we analyze the optimal choices on the part of households and firms, and we close our model by specifying a conventional form of monetary policy. Appendix A states the dynamic stochastic system of equations that are used in our quantitative analysis.

2.1 Households

There is a continuum of households and each of them consists of a large number of family members. There is assumed to be full consumption risk sharing within each household.² Each period some family members are unemployed while others work for firms. Each member has the following period utility function

$$E_t \sum_{k=0}^{\infty} \beta^k \left[\ln C_{t+k} - \chi \frac{H_{t+k}^{1+\eta}}{1+\eta} \right], \quad (1)$$

²See Merz (1995) and Andolfatto (1996).

where parameter η denotes the inverse of the labor supply elasticity, and parameter χ is a scaling parameter to be used in the calibration of our model. H_t denotes hours worked in period t , and C_t is consumption of the aggregate good.

The household is assumed to maximize the average utility of its members subject to a sequence of budget constraints of the form

$$P_t(C_t + I_t) + D_t \leq P_t R_t^K K_t + D_{t-1} R_{t-1} + P_t W_t H_t N_t + P_t B_t U_t^M + T_t, \quad (2)$$

where P_t is the price index, I_t is investment of the aggregate good, and D_t denotes riskless one-period nominal bonds with the associated gross nominal interest rate R_t . The capital stock, K_t , is rented out to firms and the real rental price of capital is R_t^K . The household's labor income results from the real wage, W_t , hours worked, H_t , and employment, N_t . We have also used the definition $U_t^M \equiv 1 - N_t$ for period t unemployment, and B_t is the real unemployment benefit. Finally, T_t denotes nominal transfers, including dividends resulting from ownership of firms. The law-of-motion of capital is of the form

$$K_{t+1} = (1 - \delta) K_t + Z_{I,t} \Psi \left(\frac{I_t}{K_t} \right) K_t, \quad (3)$$

where $Z_{I,t}$ is the level of investment-specific technology, and function $\Psi(\cdot)$ measures the capital adjustment cost. It is assumed that $\Psi(\delta) = \delta$, $\Psi'(\delta) = 1$, and $\Psi''(\delta) = \frac{-1}{\delta \epsilon_\psi}$, with parameter ϵ_ψ denoting the elasticity of the investment-to-capital ratio with respect to marginal Q, evaluated in steady state. Parameter δ is the rate of capital depreciation.

The consumer Euler equation implied by this structure takes the following standard form

$$1 = R_t E_t \left\{ \Lambda_{t,t+1} \left(\frac{P_t}{P_{t+1}} \right) \right\}, \quad (4)$$

where $\Lambda_{t,t+1} \equiv \beta \frac{C_t}{C_{t+1}}$ is the real stochastic discount factor. Moreover, we get an

optimality condition for capital accumulation

$$Q_t = E_t \left\{ \Lambda_{t,t+1} \left[Q_{t+1} \left((1 - \delta) + Z_{I,t+1} \Psi_{t+1} - Z_{I,t+1} \Psi'_{t+1} \frac{I_{t+1}}{K_{t+1}} \right) + R_{t+1}^K \right] \right\}, \quad (5)$$

where $Q_t \equiv \frac{1}{Z_{I,t} \Psi'(\frac{I_t}{K_t})}$, the marginal Q , measures in equilibrium the period t expected discounted real value of having an additional unit of capital in period $t + 1$.

2.2 Firms

There is a continuum of monopolistically competitive firms, indexed on the unit interval. Each firm i has access to the following technology

$$Y_t(i) = (Z_t N_t(i) H_t(i))^{1-\alpha} K_t(i)^\alpha, \quad (6)$$

where $N_t(i)$ is the number of employees in firm i , and $H_t(i)$ indicates hours worked by each employee, while $K_t(i)$ is the amount capital used in production. Last, Z_t is the level of neutral technology. We assume constant returns to scale and a capital share of $\alpha \in [0, 1]$.

Cost minimization on the part of households and firms implies that demand for good i is given by

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t, \quad (7)$$

where $Y_t \equiv \left(\int_0^1 Y_t(i)^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}$ is the aggregate good, and parameter ϵ is the elasticity of substitution between different varieties of goods $Y_t(i)$. Let us also note that the associated price index is $P_t \equiv \left(\int_0^1 P_t(i)^{1-\epsilon} di \right)^{\frac{1}{1-\epsilon}}$.

The law of motion of employment is given by

$$N_t(i) = (1 - s) N_{t-1}(i) + \Phi(V_t/U_t) V_t(i), \quad (8)$$

where $V_t(i)$ is the number of vacancies posted by firm i in period t , and parameter s denotes the separation rate. We have also used the definition $\Phi(V_t/U_t) \equiv$

$\omega (V_t/U_t)^{-\gamma}$, with V_t denoting aggregate vacancies, and $U_t \equiv 1 - (1 - s) N_{t-1}$ are household members looking for jobs at the beginning of period t . Parameter γ indicates the matching elasticity, and ω is a measure of the efficiency of the matching technology. We assume the following labor adjustment cost

$$G_t(i) \equiv Z_t Z_{I,t}^{\frac{\alpha}{1-\alpha}} G \left(\frac{N_t(i)}{N_{t-1}(i)} \right) N_{t-1}(i). \quad (9)$$

with $G(1) = G'(1) = 0$, and $G''(1) = \epsilon_n$, where parameter ϵ_n is the labor-adjustment cost in the log-linear approximation. Moreover there is a cost $c Z_t Z_{I,t}^{\frac{\alpha}{1-\alpha}}$ of posting a vacancy, where parameter c is a constant that is used in the calibration. Both costs are measured in units of the aggregate good. Finally, the Calvo restriction on price adjustment states that each period a lottery takes place and with probability $(1 - \theta)$ a firm gets to re-optimize its price, whereas with probability θ the firm posts its last period's price. Since households are assumed to be the ultimate owners of the firms in the economy, firms use the stochastic discount factor to discount future profits. A firm's problem therefore reads

$$\max \sum_{k=0}^{\infty} E_t \left\{ \Lambda_{t,t+k} \left[\begin{array}{l} Y_{t+k}(i) \frac{P_{t+k}(i)}{P_{t+k}} - [W_{t+k}(i) N_{t+k}(i) H_{t+k}(i) \\ + c Z_t Z_{I,t}^{\frac{\alpha}{1-\alpha}} V_{t+k}(i) + G_{t+k}(i) + R_{t+k}^K K_{t+k}(i)] \end{array} \right] \right\}$$

s.t.

$$\begin{aligned} Y_{t+k}(i) &= \left(\frac{P_{t+k}(i)}{P_{t+k}} \right)^{-\epsilon} Y_{t+k}, \\ Y_{t+k}(i) &= (Z_{t+k} N_{t+k}(i) H_{t+k}(i))^{1-\alpha} K_{t+k}(i)^\alpha, \\ N_{t+k}(i) &= (1 - s) N_{t+k-1}(i) + \Phi(V_t/U_t) V_t(i), \\ P_{t+k+1}(i) &= \begin{cases} P_{t+k+1}^*(i) & \text{with prob. } (1 - \theta) \\ P_{t+k}(i) & \text{with prob. } \theta \end{cases}. \end{aligned}$$

The first order condition for price-setting is standard

$$\sum_{k=0}^{\infty} \theta^k E_t \left\{ \Lambda_{t,t+k} Y_{t+k}(i) \left[P_t^*(i) \frac{P_t}{P_{t+k}} - \mu MC_{t+k}(i) \right] \right\} = 0, \quad (10)$$

where $\mu \equiv \frac{\epsilon}{\epsilon-1}$ denotes the frictionless markup. Firm i 's real marginal cost, $MC_t(i)$, is of the form

$$MC_t(i) = \frac{W_t(i) + H_t(i) \frac{\partial W_t(i)}{\partial H_t(i)}}{(1-\alpha) \frac{Y_t(i)}{H_t(i)N_t(i)}}, \quad (11)$$

which reflects that firms take rationally into account that with wage bargaining a marginal increase in hours worked per worker increases the real wage. At the margin, the cost of using hours worked and rented capital must be the same, which implies

$$MC_t(i) = \frac{R_t^K}{\alpha Y_t(i) / K_t(i)}. \quad (12)$$

Combining the first-order conditions for employment and vacancy posting implies

$$\begin{aligned} \Xi_t + W_t(i) H_t(i) + \frac{\partial G_t(i)}{\partial N_t(i)} &= (1-\alpha) MC_t(i) Y_t(i) / N_t(i) \\ &+ E_t \left\{ \Lambda_{t,t+1} \left[(1-s) \Xi_{t+1} - \frac{\partial G_{t+1}(i)}{\partial N_t(i)} \right] \right\}, \end{aligned} \quad (13)$$

where $\Xi_t \equiv \frac{cZ_t Z_{I,t}^{\frac{\alpha}{1-\alpha}}}{\Phi(V_t/U_t)}$ can be interpreted as the real cost of hiring one additional worker. Equation (13) reflects the fact that hiring is a forward-looking decision. The left hand side gives the marginal cost of integrating one additional worker into the workforce. It consists of the associated hiring cost, the cost of adjusting the workforce, and the wage income. The right hand side gives the marginal benefit from having an additional worker: the cost savings resulting from having a larger workforce, and the continuation value. The latter consists of future savings in hiring costs, as well as changes in the future cost of adjusting the workforce. The level of employment is a firm-specific state variable in our model. We therefore use the method in Woodford (2005) to compute the coefficient pre-multiplying the average

real marginal cost in the inflation equation. The details are given in Appendix B.

Market clearing implies that aggregate output reads

$$Y_t = C_t + I_t + Z_t Z_{I,t}^{\frac{\alpha}{1-\alpha}} \int_0^1 \left[cV_t(i) + G \left(\frac{N_t(i)}{N_{t-1}(i)} \right) N_{t-1}(i) \right] di, \quad (14)$$

while value added, GDP_t , is defined as

$$GDP_t \equiv C_t + I_t.$$

2.3 Wage Negotiation

The wage negotiation takes the form considered in Sveen and Weinke (2009). Specifically, we follow Ravenna and Walsh (2008) and Blanchard and Galí (2010) and assume that newly hired workers become productive instantaneously. The period value of a match (with firm i) for a worker, expressed in consumption units, $\widetilde{W}_t(i)$, is of the form

$$\begin{aligned} \widetilde{W}_t(i) = & W_t(i) H_t(i) - \chi C_t \frac{H_t(i)^{1+\eta}}{1+\eta} + E_t \left\{ \Lambda_{t,t+1} \left[(1-s) \widetilde{W}_{t+1}(i) \right. \right. \\ & \left. \left. + s \left(F_{t+1} \widetilde{W}_{t+1} + (1-F_{t+1}) \widetilde{U}_{t+1} \right) \right] \right\}, \end{aligned} \quad (15)$$

where $F_t \equiv \frac{\Phi(V_t/U_t)V_t}{U_t}$ is the job-finding probability, and \widetilde{U}_t is the value of being unemployed after hiring has taken place. It is given by

$$\widetilde{U}_t = B_t + E_t \left\{ \Lambda_{t,t+1} \left[F_{t+1} \widetilde{W}_{t+1} + (1-F_{t+1}) \widetilde{U}_{t+1} \right] \right\}, \quad (16)$$

where $B_t \equiv B Z_t Z_{I,t}^{\frac{\alpha}{1-\alpha}}$ is the unemployment benefit, and the value of the average match is $\widetilde{W}_t \equiv \int_0^1 \widetilde{W}_t(i) \frac{V_t(i)}{V_t} di$. The period value of the match for a worker consist of the associated real wage income taking into account the utility cost of working expressed in consumption units. In addition, the match gives a continuation value for the worker. With probability $(1-s)$ the worker will still work at firm i in period

$t + 1$, and in case the worker separates from firm i , she can find a job at another firm (with probability F_{t+1}). Otherwise, she will receive the unemployment benefit. The value of being unemployed (after hiring has taken place) can be interpreted in an analogous way. In period t the worker receives an unemployment benefit, and in addition she obtains a continuation value.

The value of a match for firms corresponds to the cost of hiring a worker

$$\tilde{J}_t = \Xi_t. \quad (17)$$

The reason is that newly hired workers become productive instantaneously so that a firm can hire another worker if negotiations break down. Nash wage bargaining implies the first-order condition

$$(1 - \phi) \tilde{J}_t = \phi \left(\tilde{W}_t(i) - \tilde{U}_t \right), \quad (18)$$

where $(1 - \phi)$ denotes the weight of workers in the bargain. This implies that all household members who work receive the same value from a match, irrespective of which firm a household member works for. This is, again, a consequence of instantaneous hiring.

Combining (15) and (16), we arrive at the following expression for the gain from working compared to being unemployed

$$\begin{aligned} \tilde{W}_t - \tilde{U}_t &= W_t(i) H_t(i) - \chi C_t \frac{H_t(i)^{1+\eta}}{1+\eta} - B_t \\ &+ E_t \left\{ \Lambda_{t,t+1} \left[(1-s)(1-F_{t+1}) \left(\tilde{W}_{t+1} - \tilde{U}_{t+1} \right) \right] \right\}. \end{aligned} \quad (19)$$

Hence any wage differences across firms result from differences in hours worked only. In fact, the real wage income compensates for the disutility derived from hours worked (expressed in consumption units), since the gain from working is equal across all firms. We can use (17) and (19) to substitute for \tilde{J}_t and $\tilde{W}_t - \tilde{U}_t$ in equation

(18). This implies

$$W_t(i) = \frac{\chi C_t \frac{H_t(i)^{1+\eta}}{1+\eta} + \Psi_t}{H_t(i)}, \quad (20)$$

where

$$\Psi_t \equiv B_t + \frac{(1-\phi)}{\phi} [\Xi_t - E_t \{ \Lambda_{t,t+1} (1-s) (1-F_{t+1}) \Xi_{t+1} \}]. \quad (21)$$

Finally, using equation (20), it can be seen that firm i 's real marginal cost satisfies

$$MC_t(i) = \frac{\chi C_t H_t(i)^\eta}{(1-\alpha) \frac{Y_t(i)}{N_t(i) H_t(i)}}. \quad (22)$$

This shows that the bargained wage is privately efficient, i.e., the marginal rate of substitution of consumption for leisure relative to labor productivity is relevant for the determination of firm i 's real marginal cost.

2.4 Monetary policy

We assume that the central bank follows a Taylor rule of the form

$$R_t = \beta^{-(1-\rho_R)} (R_{t-1})^{\rho_R} \left(\frac{P_t}{P_{t-1}} \right)^{(1-\rho_R)\phi_\pi},$$

where ρ_R is meant to indicate the degree of interest rate smoothing, and parameter ϕ_π measures the responsiveness of the nominal interest rate to changes in inflation.

2.5 Exogenous shocks

The exogenous processes Ψ_t and Z_t measure the respective levels of investment-specific and neutral technology. They are described by stationary autoregressive processes of the form

$$\ln \Psi_t = \rho_\Psi \ln \Psi_{t-1} + \varepsilon_{\Psi,t}, \quad (23)$$

$$\ln Z_t = \rho_Z \ln Z_{t-1} + \varepsilon_{Z,t}, \quad (24)$$

with $\rho_\Psi, \rho_Z \in (0, 1)$ and $\varepsilon_{\Psi,t}, \varepsilon_{Z,t}$ denoting the respective innovations in those processes. In order to be consistent with the identifying assumptions in the VARs estimated by Canova et al. (2010 and 2012) we would need to consider permanent technological shocks. It is well understood, however, that monetary DSGE models featuring permanent technological shocks need to combine a wide variety of nominal and real rigidities in order to imply an empirically plausible inflation response to those shocks (see, e.g., Smets and Wouters 2007). Our goal in the present paper is more limited. We wish to isolate the economic mechanisms through which technological shocks can affect labor market variables, and we therefore stick to a relatively simple model featuring transitory technological shocks.

2.6 Calibration

We consider a quarterly model. In our quantitative analysis the following values are assigned to the model parameters.³ Unless specified otherwise the values assigned to the model parameters are justified in Sveen and Weinke (2009) and the references therein. We let β be 0.99, which implies an annual steady state real interest rate of about 4 per cent. The elasticity of substitution between goods, ϵ , is set to 7. This implies a steady-state mark-up of about 20 per cent. Our baseline value for the Calvo parameter, θ , is 0.75, i.e., firms change their prices on average once a year. As far as monetary policy is concerned, we set $\tau_\pi = 1.5$ and $\rho_r = 0.95$. The labor supply elasticity, $1/\eta$, takes the value 0.3. The matching function elasticity, γ , is set to 0.6. The separation rate, s , is assumed to take the value 0.1, and the unemployment benefit, B , is set to 40% of steady state real labor income. The labor adjustment cost, ϵ_n , takes the value 2, and the bargaining power parameter, ϕ , equals 0.5. We impose that hours worked in steady state correspond to 1/3 of available time. Period unemployment is set to 0.06, and we let the quarterly job-filling rate be 0.7. This is achieved by an appropriate choice of parameters χ, ω ,

³To solve the dynamic stochastic system of equations we use Dynare (www.dynare.org). Matlab code for our implementation of Woodford's (2005) method is available upon request.

and c . For those parameters not contained in Sveen and Weinke (2009) we also choose conventional values. Specifically, the depreciation rate, δ , is assumed to take the value 0.025, and the capital share, α , is set to 0.33. The capital adjustment cost parameter, ϵ_ψ , is given by $\frac{1}{20*\delta}$. Finally, we assume $\rho_\Psi = \rho_Z = 0.9$, a setting associated with persistent technological processes.

3 Results

Our main result regards the relative importance of the two margins of labor adjustment in response to the two alternative forms of technological shocks under consideration. This is illustrated in figures 1 and 2. They show, respectively, the dynamic response of several macro variables to a one standard-deviation shock to neutral and investment-specific technology. The rate of inflation is annualized. All other variables are measured as the respective log deviation of the original variable from its steady state value.

[Fig 1 and 2 about here]

As illustrated in figure 1, hours decrease in response to a positive neutral technology shock. That result accords with the evidence in Galí (1999). Most importantly, the fact that adjustment occurs primarily along the extensive margin is in line with the empirical results in Canova et al. (2010, 2012). In a way consistent with standard results in the New Keynesian literature (see, e.g., Galí 2015, pp. 72) inflation and the real wage decrease in response to a positive neutral technology shock, even though output expands. In the context of our model, the output response takes a hump-shaped form. The reason is the sluggish response of aggregate demand to the neutral technology shock, which is a consequence of price stickiness. In particular, capital builds up only gradually for this economic reason. Figure 2 displays impulse responses for the same macro variables, as implied by an investment-specific technology shock. Consistent with the evidence in Fisher (2006) hours increase in

response to a positive investment-specific technology shock, and also in this case, our theoretical result is consistent with the corresponding empirical findings in Canova et al. (2010, 2012). In fact, conditional on an investment-specific technology shock our model predicts that the adjustment occurs predominantly through the intensive margin of labor adjustment. A key aspect of that shock is that firms can only take advantage of it by investing. This explains why investment, output, inflation and the real wage all increase in the aftermath of an investment-specific technology shock.

The intuition behind the relative importance of the two margins of labor adjustment in response to the two alternative forms of technological shocks under consideration is straightforward. Employment relationships are costly to establish in our model. The extensive margin of labor adjustment to an economic shock is therefore quantitatively important, if the shock makes a long-term adjustment worthwhile. But this is the case for a persistent shock to total factor productivity. On the other hand, an expansionary investment-specific technology shock incentivizes firms to use the more flexible hours margin to adjust to the shock. The reason is that firms can only take advantage of this shock by investing. But additional investment demand in the economy creates a short-run extra need for labor input, which makes it optimal for firms to use predominantly the more flexible hours margin in their adjustment to the shock.

It is instructive to compare those economic mechanisms to the ones proposed by Michelacci and Lopez-Salido (2007). In their model technological shocks can prompt waves of Schumpeterian destruction. The idea is that technological progress can make old jobs obsolete. In the short-run, employment can therefore decrease in response to a positive technological shock. The extent to which this occurs depends on various other aspects of the model. In particular, the degree of labor market frictions is important for the quantitative relevance of relocations between obsolete and technologically advanced jobs. Moreover, the extent to which investment is needed to bring about technological improvement of existing jobs matters for the short-run employment response to a technological shock. The reason is that the increase in

the marginal utility of consumption (associated with an increase in investment) increases the value of an existing job, for any given level of technology. The authors show that in response to a positive neutral technology shock employment decreases, whereas it increases in response to an investment-specific technology shock. This is an interesting theoretical explanation of the empirical evidence on the propagation of technological shocks on labor market variables. The present paper offers, however, an alternative economic mechanism to explain those empirical regularities, and it is fair to say that compared with Michelacci and Lopez-Salido (2007) our explanation combines features which are standard in the DSGE models that are nowadays routinely used by researchers inside and outside the academic world to analyze a wide range of issues related to business cycle fluctuations. In particular, the economic mechanism analyzed in this paper relies on demand-constrained firms setting prices in a staggered fashion. The reason is that labor adjustment to technological shocks along both margins will only be conducted according to the incentives analyzed above, if a firm has a limited ability to affect demand over the planning horizon for a long-term employment decision. In fact, to the extent that prices are fully flexible, labor market variables react very little to technological shocks. This is illustrated in figures 3 and 4.

[Fig 3 and 4 about here]

Figure 3 displays the dynamic effects of a positive neutral technology shock in a flexible price version of our model. Those results are reminiscent of the unemployment volatility puzzle analyzed by Hall (2005), Shimer (2005), Costain and Reiter (2008) and Pissarides (2009).⁴ They show that, in the context of RBC models, search frictions generally cannot explain the cyclical behavior of unemployment

⁴Pissarides (2009) coined the term "unemployment volatility puzzle". His main focus is the role of wage stickiness à la Hall (2005) and Hall and Milgrom (2008) in that context. He also observes: "Costain and Reiter (2008) noted, in a paper that anticipated to some extent both the Shimer [2005] critique and the Hagedorn and Manovskii (2008) response, that if nonmarket returns are high, the response of unemployment to labor-market policy, in particular unemployment insurance, is too large."

(and vacancies) in response to neutral technological shocks. Also in the case of a positive investment-specific technology shock, illustrated in figure 3, the response of the labor market variables is relatively muted compared with the corresponding outcome in the baseline version of our model. This is in line with some of the findings in Sveen and Weinke (2008). They point at the importance of demand shocks in accounting for labor market dynamics. The quantitative importance of those shocks is, however, enhanced by price stickiness, as analyzed there. A related point regards the role of monetary policy. More concretely, by fully stabilizing the price level, monetary policy can replicate the flexible price equilibrium allocation in the context of our baseline sticky price model. This is a standard result, which is often referred to as divine coincidence (see, e.g., Galí 2015, pp. 103). By increasing the size of policy parameter ϕ_π , i.e., the responsiveness of the nominal interest rate to changes in inflation, the central bank can approximate that outcome in our model.

4 Conclusion

Starting with a seminal contribution by Galí (1999), the effect of technological shocks on hours worked has received much attention in macroeconomics. In particular, Canova et al. (2010 and 2012) have estimated the propagation of technological shocks on labor market variables by allowing adjustment along both the intensive margin (i.e., hours worked) and the extensive margin (i.e., employment). Using an SVAR model identified through long-run restrictions as in Fisher (2006), they estimate the dynamic consequences of both investment-specific and neutral technology shocks. Interestingly, they find that the two margins of labor adjustment are used to a very different extent depending on the nature of the technological shock under consideration. More concretely, labor input contracts along both margins in the aftermath of a positive neutral technology shock, and the largest share of that adjustment takes place along the extensive margin. By way of contrast, investment-specific technology shocks have an expansionary effect, which results predominantly

from adjustments along the intensive margin.

The present paper shows that the empirical evidence described above can be explained in the context of a New Keynesian model featuring endogenous capital accumulation combined with labor market frictions. We therefore offer an alternative to the Schumpeterian economic mechanism developed in Michelacci and Lopez-Salido (2007). This is interesting, we believe, because our explanation combines features which are standard in the DSGE models that are nowadays routinely used by researchers inside and outside the academic world to analyze a wide range of issues related to business cycle fluctuations. Ultimately, structural econometric work will be needed in order to assess the relative quantitative relevance of those (and potentially other) economic mechanisms. This is an avenue of our future research.

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Appendix A: Linearized Equilibrium Conditions

In what follows we consider a log-linear approximation to the equilibrium dynamics around a zero inflation steady state. Unless stated otherwise lower case letters denote the log-deviation of the original variable from its steady state value. The consumption Euler equation reads

$$c_t = E_t \{c_{t+1}\} - (rr_t - \rho), \quad (25)$$

where parameter ρ denotes the household's time preference rate and $rr_t \equiv r_t - E_t \pi_{t+1}$ is the real interest rate. Up to the first order aggregate production is given by

$$y_t = (1 - \alpha)(z_t + n_t + h_t) + \alpha k_t. \quad (26)$$

Linearizing and aggregating the law of motion of capital gives

$$k_{t+1} = (1 - \delta)k_t + \delta i_t + \delta z_{I,t}, \quad (27)$$

and the first-order conditions associated with investment and capital can be log-linearized as

$$q_t = \beta E_t \{q_{t+1}\} + (1 - \beta(1 - \delta)) E_t \{r_{t+1}^K\} + \beta \delta \rho_I z_{I,t} - (rr_t - \rho), \quad (28)$$

$$i_t - k_t = \epsilon_\psi (q_t + z_{I,t}), \quad (29)$$

where the following relationship holds true

$$r_t^K = mc_t + (y_t - k_t). \quad (30)$$

Aggregating the linearized law of motion of firm-level employment results in

$$n_t = (1 - s)n_{t-1} + \frac{\Phi(V/U)V}{N} [(1 - \gamma)v_t + \gamma u_t], \quad (31)$$

where we have used the notation that a variable without a time subscript denotes the steady state value of that variable. Linearized search unemployment reads

$$u_t = - (1 - s) \frac{N}{U} n_{t-1}. \quad (32)$$

Period unemployment is given by

$$u_t^m = - \frac{N}{U^M} n_t. \quad (33)$$

Aggregating and linearizing the first order condition for firm-level employment implies

$$\begin{aligned} \Xi \xi_t + \epsilon_n \Delta n_t + WH (w_t + h_t) &= \frac{1}{\mu} \frac{Y}{N} (m c_t + y_t - n_t) + \epsilon_n \beta E_t \{ \Delta n_{t+1} \} \\ &+ (1 - s) \beta \Xi E_t \{ (r r_t - \rho) + \xi_{t+1} \}, \end{aligned} \quad (34)$$

where Δ is the difference operator and

$$\xi_t = \gamma (v_t - u_t) + z_t + \frac{\alpha}{1 - \alpha} z_{I,t}.$$

The following relationships holds true

$$f_t = (1 - \gamma) (v_t - u_t). \quad (35)$$

The real wage is given by

$$w_t = \frac{\chi C^{\frac{H^{1+\eta}}{1+\eta}}}{WH} (c_t + (1 + \eta) h_t) - h_t + \frac{\Psi}{WH} \psi_t, \quad (36)$$

and

$$\begin{aligned} \psi_t &= z_t + \frac{\alpha}{1 - \alpha} z_{I,t} + \frac{(1 - \phi) \Xi}{\phi \Psi} \{ \xi_t + \beta (1 - s) [(1 - F) (r r_t - \rho) \\ &+ E_t \{ F f_{t+1} - (1 - F) \xi_{t+1} \}] \}. \end{aligned} \quad (37)$$

The real marginal cost reads

$$mc_t = c_t + \eta h_t - (y_t - n_t - h_t). \quad (38)$$

The following inflation equation is derived

$$\pi_t = \beta E_t \pi_{t+1} + \kappa mc_t, \quad (39)$$

where parameter κ is computed numerically using the method outlined in Woodford (2005). Market clearing implies

$$y_t = \frac{C}{Y} c_t + \frac{I}{Y} i_t + c \frac{V}{Y} \left(v_t + z_t + \frac{\alpha}{1 - \alpha} z_{I,t} \right), \quad (40)$$

and value added reads

$$gdp_t = \frac{C}{GDP} c_t + \frac{I}{GDP} i_t.$$

Last, monetary policy is given by

$$r_t = \rho_r r_{t-1} + (1 - \rho_r) [\rho + \tau_\pi \pi_t] + e_{rt}. \quad (41)$$

Appendix B: Computational Algorithm

We posit rules for price-setting and for employment

$$\widehat{p}_t^*(i) = \widehat{p}_t^* + \kappa_1 \widehat{n}_{t-1}(i), \quad (42)$$

$$\widehat{n}_t(i) = \xi_1 \widehat{p}_t(i) + \xi_2 \widehat{n}_{t-1}(i). \quad (43)$$

where $\widehat{N}_t(i) \equiv \frac{N_t(i)}{N_t}$, $\widehat{P}_t(i) \equiv \frac{P_t(i)}{P_t}$ denote, respectively, firm i 's relative price and its relative to average employment. We have also used the definitions $\widehat{P}_t^*(i) \equiv \frac{P_t^*(i)}{P_t}$ and $\widehat{P}_t^* \equiv \frac{P_t^*}{P_t}$, where P_t^* is the average newly set price.

Let us first impose stability. Invoking the pricing and employment rules, as well as the definition of the price index we obtain

$$\begin{bmatrix} E_t \widehat{p}_{t+1}(i) \\ E_t \widehat{n}_{t+1}(i) \end{bmatrix} = A \begin{bmatrix} \widehat{p}_t(i) \\ \widehat{n}_t(i) \end{bmatrix}, \quad (44)$$

where $A \equiv \begin{bmatrix} 1 & 0 \\ -\xi_1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \theta & (1-\theta)\kappa_1 \\ 0 & \xi_2 \end{bmatrix} = \begin{bmatrix} \theta & (1-\theta)\kappa_1 \\ \theta\xi_1 & \kappa_1\xi_1(1-\theta) + \xi_2 \end{bmatrix}$. Stability requires that all roots of matrix A are inside the unit circle. Our goal is to find conditions for the unknown coefficients in the rules. To this end we first express key firm level variables (production, hours worked, capital and the real marginal cost) as a function of the two variables in the rules. We have

$$\begin{bmatrix} \widehat{y}_t(i) \\ \widehat{h}_t(i) \\ \widehat{k}_t(i) \\ \widehat{mc}_t(i) \end{bmatrix} = B \begin{bmatrix} \widehat{p}_t(i) \\ \widehat{n}_t(i) \end{bmatrix}, \quad (45)$$

where

$$\begin{aligned}
B &\equiv \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & -(1-\alpha) & -\alpha & 0 \\ 1 & 0 & -1 & 1 \\ 1 & -(1+\eta) & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} -\epsilon & 0 \\ 0 & 1-\alpha \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \\
&= \frac{1}{1+\alpha\eta} \begin{bmatrix} -\epsilon(1+\alpha\eta) & 0 \\ -\epsilon & -1 \\ -\epsilon(1+\eta) & -(1-\alpha)\eta \\ -\epsilon\eta(1-\alpha) & -\eta(1-\alpha) \end{bmatrix}
\end{aligned}$$

With those preparations at hand, we next consider the linearized equation for the relative to average employment at the firm level.

$$\Delta \widehat{n}_t(i) = \beta E_t \{ \Delta \widehat{n}_{t+1}(i) \} + \frac{1}{\zeta_n} \widehat{h}_t(i), \quad (46)$$

where $\zeta_n \equiv \frac{\mu N \epsilon_n}{(1-\alpha)Y} \frac{1}{\eta}$. We therefore have

$$\left(1 + \beta - \beta(\kappa_1 \xi_1 (1-\theta) + \xi_2) - \frac{b_{22}}{\zeta_n} \right) \widehat{n}_t(i) = \left(\beta \theta \xi_1 + \frac{b_{21}}{\zeta_n} \right) \widehat{p}_t(i) + \widehat{n}_{t-1}(i), \quad (47)$$

which imposes the following two constraints on the undetermined coefficients ξ_1 and ξ_2 in the employment rule

$$\begin{aligned}
\xi_1 &= \xi_2 \left(\beta \theta \xi_1 + \frac{b_{21}}{\zeta_n} \right), \\
\xi_2 &= \frac{1}{1 + \beta - \beta(\kappa_1 \xi_1 (1-\theta) + \xi_2) - \frac{b_{22}}{\zeta_n}}.
\end{aligned}$$

Last, we consider price-setting. We can write the newly set price chosen by firm i

as follows

$$\widehat{p}_t^*(i) = \sum_{j=1}^{\infty} (\beta\theta)^j E_t \pi_{t+j} + (1 - \beta\theta) \sum_{j=0}^{\infty} (\beta\theta)^j E_t m c_{t+j} + (1 - \beta\theta) \sum_{j=0}^{\infty} (\beta\theta)^j E_t \widehat{m} c_{t+j}(i).$$

Using equation (45) we have

$$\sum_{j=0}^{\infty} (\beta\theta)^j E_t \widehat{m} c_{t+j}(i) = b_{41} E_t \sum_{j=0}^{\infty} (\beta\theta)^j (\widehat{p}_t^*(i) - \pi_{t,t+j}) + b_{42} E_t \sum_{j=0}^{\infty} (\beta\theta)^j \widehat{n}_{t+j}(i).$$

Using the above rules as well as the Calvo assumption we find

$$\begin{aligned} \widehat{n}_{t+j}(i) &= \xi_1 \widehat{n}_{t+j-1}(i) + \xi_2 (\widehat{p}_t^*(i) - \pi_{t,t+j}) \\ &= \xi_1 [\xi_1 \widehat{n}_{t+j-2}(i) + \xi_2 (\widehat{p}_t^*(i) - \pi_{t,t+j-1})] + \xi_2 (\widehat{p}_t^*(i) - \pi_{t,t+j}). \end{aligned}$$

We therefore have

$$\begin{aligned} \sum_{j=0}^{\infty} (\beta\theta)^j E_t \widehat{n}_{t+j}(i) &= \frac{\xi_1}{1 - \xi_1 \beta\theta} \widehat{n}_{t-1}(i) + \frac{\xi_2}{(1 - \beta\theta)(1 - \xi_1 \beta\theta)} \widehat{p}_t^*(i) \\ &\quad - \frac{\xi_2}{(1 - \beta\theta)(1 - \xi_1 \beta\theta)} \sum_{j=1}^{\infty} (\beta\theta)^j E_t \pi_{t+j}. \end{aligned}$$

Combining the last equations and invoking the Calvo assumption, i.e., noting that the average value of $\widehat{n}_{t-1}(i)$ is zero in the group of time t price setters we have

$$\widehat{p}_t^*(i) = \widehat{p}_t^* + \frac{1}{1 - b_{41} - \frac{b_{42} \xi_2}{1 - \xi_1 \beta\theta}} \frac{b_{42} \xi_1 (1 - \beta\theta)}{1 - \xi_1 \beta\theta} \widehat{n}_{t-1}(i). \quad (48)$$

We can therefore impose the following condition on the unknown parameter in the pricing rule

$$\kappa_1 = \frac{1}{1 - b_{41} - \frac{b_{42} \xi_2}{1 - \xi_1 \beta\theta}} \frac{b_{42} \xi_1 (1 - \beta\theta)}{1 - \xi_1 \beta\theta}.$$

The average newly set price reads

$$\widehat{p}_t^* = \sum_{j=1}^{\infty} (\beta\theta)^j E_t \pi_{t+j} + \frac{1-\beta\theta}{\omega} \sum_{j=0}^{\infty} (\beta\theta)^j mc_{t+j}, \quad (49)$$

where

$$\omega \equiv \frac{(1+\epsilon\eta)(1-\xi_2\beta\theta) + \eta\xi_1}{(1-\xi_2\beta\theta)}.$$

Solving the last equation forward and invoking the linearized price index gives

$$\pi_t = \beta E_t \{\pi_{t+1}\} + \kappa mc_t, \quad (50)$$

where

$$\kappa \equiv \frac{(1-\beta\theta)(1-\theta)}{\theta} \frac{1}{\omega}.$$

For candidate parameter values which satisfy the stability requirement we therefore solve the following system

$$\begin{aligned} \kappa_1(\xi_1, \xi_2) &= \frac{\xi_2(1-\beta\theta)\eta}{(\xi_2\beta\theta - 1)(1+\epsilon\eta) - \xi_1\eta}, \\ \xi_1 &= \frac{\frac{\xi}{\zeta}\xi_2}{\xi_2\beta\theta - 1}, \\ 0 &= 1 - (1+\beta)\xi_2 - \frac{\xi_2}{\zeta} + \beta\xi_2^2 + \beta\xi_1\xi_2(1-\theta)\kappa_1. \end{aligned}$$

This pins down the coefficients (ξ_1, ξ_2, κ_1) .

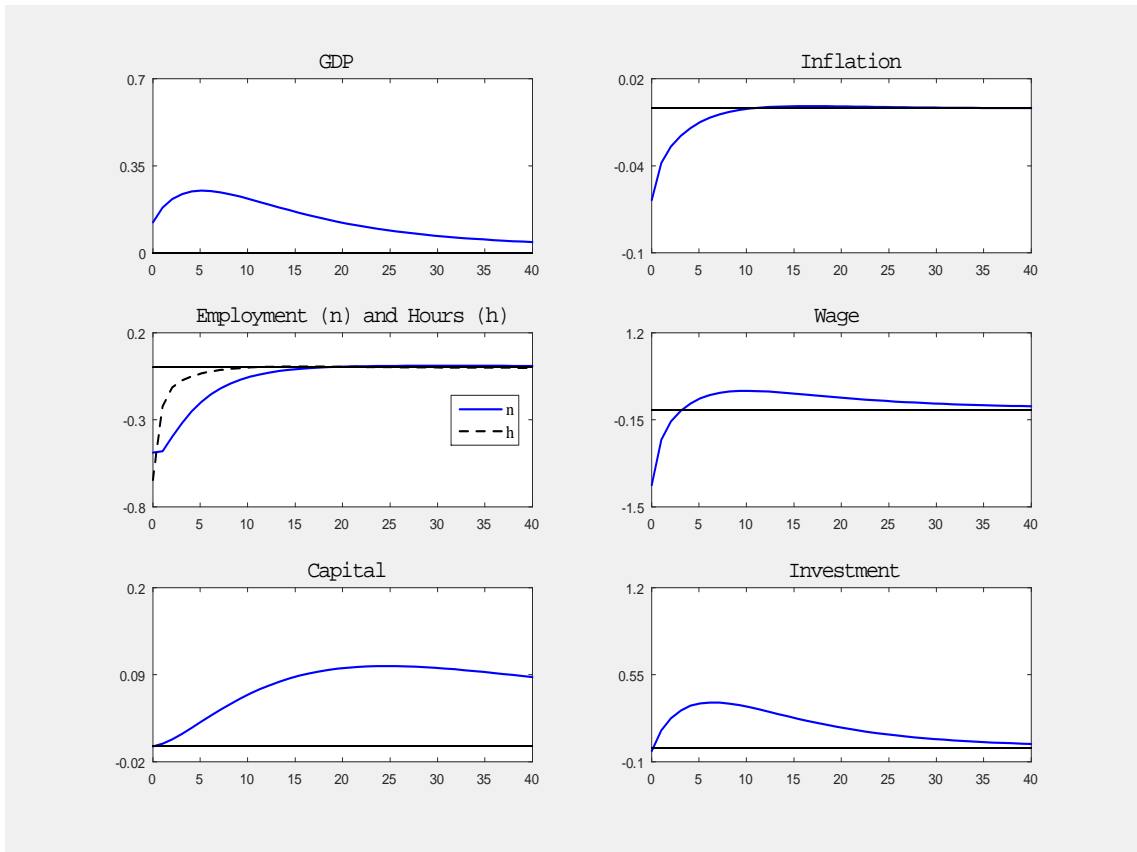


Fig. 1. Neutral Technology Shock.

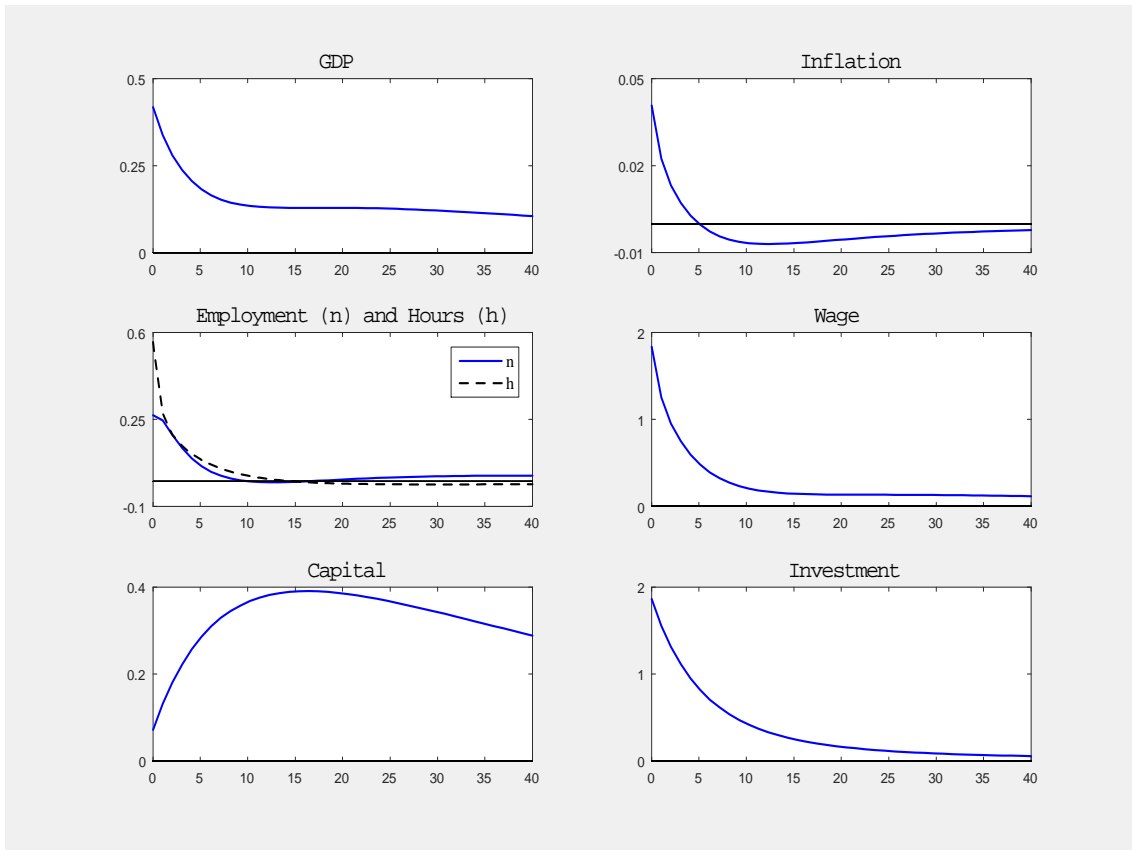


Fig 2. Investment-Specific Technology Shock.

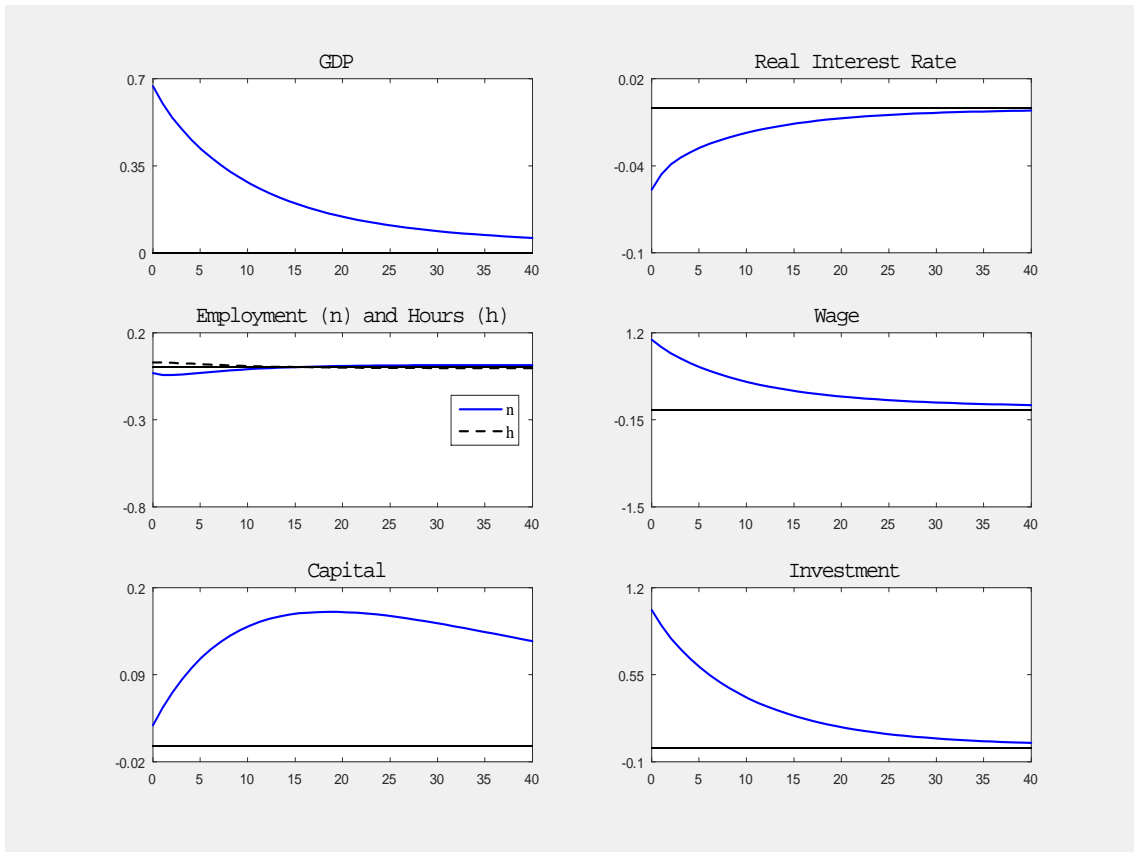


Fig. 3. Neutral Technology Shock. Flexible Prices.

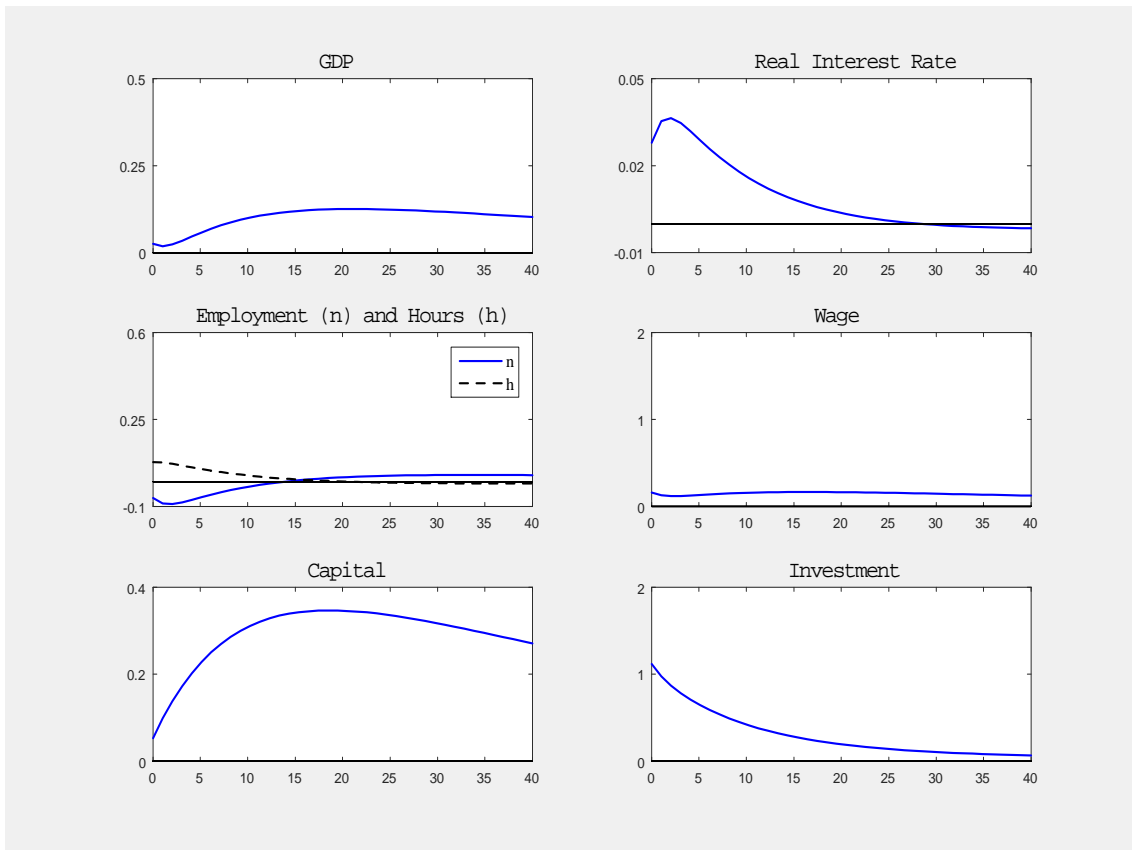


Fig 4. Investment-Specific Technology Shock. Flexible Prices.