Frictions in DSGE Models: Revisiting New Keynesian vs New Classical Results

Renato Faccini
Queen Mary, University of London and Centre for Macroeconomics (LSE)*

Eran Yashiv
Tel Aviv University, Centre for Macroeconomics (LSE), and CEPR†

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Abstract

We study the interactions of convex hiring and investment frictions and price frictions in a DSGE model. These turn out to produce major changes in outcomes of all key macroeconomic variables, shedding new light on New Keynesian vs New Classical results.

We examine technology and monetary shocks under alternative specifications of the two kinds of frictions. While we reproduce the well-known finding whereby introducing only price frictions breaks money neutrality and turns the response of employment to technology shocks from positive to negative, when we add hiring and investment frictions we find, inter alia, that:

(*i*) Introducing even a moderate amount of hiring frictions in the New-Keynesian model offsets the effects of price frictions, making a monetary expansion at least neutral. However this is not the result of full flexibility but rather of a confluence of frictions.

(*ii*) With the cited frictions there is a positive response of employment to technology shocks.

(*iii*) A version of the New-Keynesian model, whereby hiring frictions reflect conservative estimates of training costs, produces impulse responses to monetary and technology shocks that are virtually identical to those obtained in the new classical model with the same hiring frictions.

(*iv*) Interacting price frictions with hiring or investment frictions generates endogenous wage rigidity by smoothing the response of the marginal rate of substitution between consumption and labor to shocks.

Keywords: New classical model, New-Keynesian model; hiring and investment frictions, price frictions; DSGE; business cycles; endogenous wage rigidity

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*Email: r.faccini@qmul.ac.uk

†Email: yashiv@post.tau.ac.il

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1 Introduction

This paper studies the interaction of convex hiring and investment frictions and price frictions in a DSGE model. This examination turns out to produce major changes in outcomes of all key macroeconomic variables. Specifically, we examine technology and monetary shocks under alternative specifications of the two sets of frictions.

Special cases include the New Classical benchmark with no frictions, and the New-Keynesian model with only price frictions.

These two dimensions of frictions have been underlying three major strands of literature: price frictions are the bedrock of New-Keynesian models, which embedded them in DSGE frameworks, as surveyed by Woodford (2003), Gali (2008) and Christiano, Trabandt and Walentin (2010); labor frictions lie at the foundations of the search model of Diamond, Mortensen and Pissarides (DMP; see Pissarides (2000) and Rogerson and Shimer (2011) for surveys); capital frictions underlie the Tobin's q literature (see Chirinko (1993) and Smith (2008) for surveys). We model convex price adjustment frictions following Rotemberg (1982) and labor and capital frictions as convex hiring and investment costs, following Merz and Yashiv (2007) and Yashiv (2014).

We reproduce the well-known finding whereby introducing *only* price frictions breaks money neutrality and turns the response of employment to technology shocks from positive to negative. But when we add hiring and investment frictions we find that:

(*i*) Introducing even a moderate amount of hiring frictions in the New-Keynesian benchmark offsets the effects of price frictions, making money at least neutral. However this is not the result of full flexibility but rather of a confluence of frictions.

(*ii*) In this case there is a positive response of employment to technology.

(*iii*) A version of the New-Keynesian model, where hiring frictions are calibrated to reflect conservative estimates of training costs, produces impulse responses to monetary and technology shocks that are virtually identical to those obtained in the New Classical model. Investment frictions also contribute to dampen the mechanism at work in the New-Keynesian model, but for reasonable parameterizations their impact is not strong enough to restore the classical dichotomy.

(*iv*) Interacting price frictions with hiring or investment frictions generates endogenous wage rigidity by smoothing the response of the marginal rate of substitution between consumption and labor to shocks.

These results are consistent with VAR evidence by Uhlig (2005) who, based on an agnostic identification scheme, concludes that a monetary stimulus is as likely to increase output as to decrease it. Moreover, for the same parameter values, the model generates countercyclical marginal costs conditional on monetary shocks, which is in line with recent evidence by Nekarda and Ramey (2013) and in contrast with standard predictions obtained in the textbook New-Keynesian model with a frictionless labor market. Similar analysis on the effects of investment frictions suggests that these costs also dampen the mechanism at work in the baseline New-Keynesian model, *but*, as noted, to a lesser extent.

The mechanism governing the interaction between price frictions and hiring and investment frictions works in two ways:

First, price frictions affect the reaction of hiring and investment to changes in the value of jobs and capital via the marginal cost. This channel is absent in real models of the labor market, such as the canonical DMP model, and in Tobin's Q models, where there is no role for marginal costs.

Second, hiring and investment frictions affect the reaction of hiring and investment to changes in the marginal cost. This channel is absent in standard New Keynesian models with frictionless labor and capital markets and offsets the mechanism at work in this class of models.

It is worth emphasizing that hiring and investment frictions *do not* operate trivially by smoothing the response of hiring and investment. So the results do not follow from the assumption that frictions in labor and capital markets are large, so quantities cannot respond. Rather, the relative price effect on capital and job values produces *non-trivial* dynamics, whereby hiring (and investment) increase with labor (and capital) frictions. Finally, we show that interacting price frictions with hiring or investment frictions generates endogenous wage rigidity by smoothing the response of the marginal rate of substitution between consumption and labor to shocks.

It is also important to emphasize that the results are *not* a comeback to the New Classical/RBC approach with a stress on supply and technology shocks, as opposed to demand shocks. First, the mechanisms in question involve a confluence of frictions, not flexibility. Second, recent papers have shown that technology shocks may be the result of demand shocks (see Bai, Rıos-Rull, and Storesletten (2012)).

The paper is organized as follows. Section 2 presents the model, Section 3 discusses the calibration and shows impulse responses. Section 4 introduces our examination of the role of each type of frictions. Section 5 explores the interaction between price frictions and hiring frictions, while Section 6 investigates the interactions between price frictions and investment frictions. Section 7 concludes.

2 The Model

2.1 The Set-Up

We propose a DSGE model with both hiring and investment frictions, as in Merz and Yashiv (2007) and Yashiv (2014), and price frictions, as in New-Keynesian models with capital. The model features three sources of frictions: price adjustment costs, costs of hiring workers and costs of installing capital. Absent all frictions, the model boils down to the benchmark New Classical model. Introducing price frictions into the otherwise frictionless model yields the New-Keynesian benchmark, and introducing hiring or investment frictions over the New-Keynesian benchmark allows us to analyze how the interplay between these frictions affects the propagation of technology and monetary shocks. In the spirit of simplicity, our modeling strategy deliberately abstracts from all other frictions and features that are quite prevalent in DSGE models and which are typically introduced to enhance propagation and improve statistical fit: namely, habits in consumption, variable capacity utilization, wage rigidities etc.

In what follows we look in detail at households, two types of firms, the monetary authority and the aggregate economy.

2.2 Households

The representative household comprises a unit measure of workers searching for jobs in a frictional labor market. At the end of each time period workers can be either employed or unemployed; we therefore abstract from participation decisions and from variation of hours worked on the intensive margin.[1] The household enjoys utility from the aggregate consumption index C_t and disutility from employment, N_t. Employed workers earn the nominal wage W_t and hold nominal bonds denoted by B_t. Both variables are expressed in units of consumption, which is the numeraire. The budget constraint is:

$$P_t C_t + \frac{B_{t+1}}{R_t} = W_t N_t + B_t + \Upsilon_t, \tag{1}$$

where $R_t = (1 + i_t)$ is the gross nominal interest rate, P_t is the price of the consumption good and Υ_t is a lump sum component of income which includes dividends from ownership of firms and government transfers.

The labor market is frictional and workers who are unemployed at the beginning of each period t are denoted by U_t^0. It is assumed that these unemployed workers can start working in the same period if they find a job with probability $x_t = \frac{H_t}{U_t^0}$, where H_t denotes the total number of matches. It follows that the workers who remain unemployed for the rest of the period, denoted by U_t, is $U_t = (1 - x_t)U_t^0$. Consequently, the evolution of aggregate employment N_t is:

$$N_t = (1 - \delta_N)N_{t-1} + x_t U_t^0, \tag{2}$$

where δ_N is the separation rate.

The intertemporal problem of the households is to maximize the discounted present value of current and future utility:

$$\max_{C_{t+j}} E_t \sum_{j=0}^{\infty} \beta^j \left(\ln C_{t+j} - \frac{\chi}{1+\varphi} N_{t+j}^{1+\varphi} \right),$$

subject to the budget constraint (1) and the law of motion of employment (2). The parameter $\beta \in (0, 1)$ denotes the discount factor, φ is the inverse Frisch elasticity of labor supply and χ is a

[1] As shown in Rogerson and Shimer (2011), most of the fluctuations in US total hours worked at business cycle frequencies are driven by the extensive margin, so our model deliberately abstracts from other margins of variation.

scale parameter governing the disutility of work.

Denoting by λ_t the Lagrange multiplier associated with the budget constraint, the first order necessary conditions and co-states are:

$$\lambda_t = \frac{1}{P_t C_t}, \tag{3}$$

$$\frac{1}{R_t} = \beta E_t \frac{P_t C_t}{P_{t+1} C_{t+1}}, \tag{4}$$

$$V_t^N = \frac{W_t}{P_t} - \chi N_t^{\varphi} C_t - \frac{x_t}{1 - x_t} V_t^N + \beta \left(1 - \delta_N\right) E_t \frac{C_t}{C_{t+1}} V_{t+1}^N, \tag{5}$$

where equation (4) is the standard Euler equation and equation (5) is the marginal value of a job to the household net of the value of search. This term is equal to the real wage, net of the opportunity cost of work, $\chi N_t^{\varphi} C_t$, and the flow value of search for unemployed workers, plus a continuation value. It is worth noting that relative to the DMP model, where the opportunity cost of work is assumed to be constant, deriving the net value of employment from a standard problem of the household implies that this opportunity cost equals the marginal rate of substitution between consumption and leisure. As we show later in the text, this feature of the model is key in generating endogenous real wage rigidity in the presence of hiring or investment frictions. It is also worth noting that in a model with no hiring frictions, where employment generates no rents and thus $V_t^N = 0$, the marginal rate of substitution equals the real wage: $\frac{W_t}{P_t^C} = \chi N_t^{\varphi} C_t$, which determines labor supply.

2.3 Firms

We assume two types of firms: intermediate producers and final good producers. Intermediate producers hire labor and invest in capital to produce a homogeneous product, which is then sold to final producers in perfect competition. Final producers transform each unit of the homogeneous product into a unit of a differentiated product facing price rigidities *à la* Rotemberg (1982). This separation between intermediate and final goods firms is often assumed to get around the difficulties that arise whenever the bargaining problem and the price setting decisions are concentrated in the same firm. It is assumed that the same bundle of final goods is used for consumption and investment purposes. So output, consumption and investment have the same price, which is denoted by P_t. Under the common Dixit-Stigliz aggregator of differentiated goods, the expenditure minimizing price index associated with the output index is

$$P_t = \left(\int_0^1 P_t\left(i\right)^{1-\epsilon} di \right)^{1/(1-\epsilon)},$$

where $P_t\left(i\right)$ is the price of a variety i and ϵ denotes the elasticity of substitution.

Intermediate Goods Producers

A unit measure of intermediate goods producers sell homogeneous goods to final producers in perfect competition. Intermediate firms combine physical capital, K, and labor, N, in order to produce intermediate output goods, Z. The constant returns to scale production function is $f(A_t, N_{t,}K_{t-1}) = A_t N_t^{\alpha} K_{t-1}^{1-\alpha}$, where A_t is a standard TFP shock that follows the stochastic process $lnA_{t+1} = \rho_a \ln A_t + e_t^a$, with $e_t^a \sim N(0, \sigma_a)$. Following a convention in DSGE modelling, we have assumed that newly installed capital becomes effective only with a one (quarter) period lag.

It is assumed that hiring and investment are costly activities. We postulate a frictions costs function g, capturing the different frictions in the hiring and investment processes. Specifically, we think of hiring costs as the disruption in economic activity associated with worker recruitment. These costs reflect training costs, and other costs that are incurred after a worker is hired, and are not sunk by the time the match is formed. Typically, labor frictions are modelled as vacancy posting costs, which are sunk at the time of bargaining. As reported in Silva and Toledo (2009) and discussed in more detail below, training costs are considerably larger than the costs of advertising a vacancy, and include the time spent by managers and team-workers to instruct new hires, which is a drag on their ability to produce. Investment involves implementation costs, financial premia on certain projects, capital installation costs, learning the use of new equipment, etc. Both activities may involve, in addition to production disruption, the implementation of new organizational structures within the firm and new production techniques; see Alexopoulos (2011) and Alexopoulos and Tombe (2012). In sum g is meant to capture all the frictions involved in getting newly employed workers to work and capital to operate in production, and not, say, just capital adjustment costs or vacancy costs. All these activities are captured by the friction cost function $g(I_t, K_{t-1}, H_t, N_t)$, where I denotes investment, and H denotes hires.[2]

These costs are thought of as forgone output. Following Merz and Yashiv (2007) we assume that the friction cost function is constant returns to scale and is increasing in each of the firm's decision variables.

$$g(I_t, K_{t-1}, H_t, N_t) = \left[\frac{e_1}{2} \left(\frac{I_t}{K_{t-1}} \right)^2 + \frac{e_2}{2} \left(\frac{H_t}{N_t} \right)^2 \right] A_t N_t^{\alpha} K_{t-1}^{1-\alpha}. \tag{6}$$

We assume quadratic costs in line with estimates by Yashiv (2014).[3] As shown in Section (3.1), this convexity implies that large swings in the hiring rates do not imply large deviations of the marginal hiring cost relative to its steady-state value.

The net output of a representative firm at time t is:

$$Z_t = f(A_t, N_{t,}K_{t-1}) - g(I_t, K_{t-1}, H_t, N_t).$$

[2] This formulation of frictions/costs is consistent with the Stole and Zweibel (1996) and Cahuc, Marque and Wasmer (2008) frameworks of intra-firm bargaining that we use (see in particular the discussion on pages 376-378 and 384-387 in the former).

[3] *A rationale for the use of such functional forms, emphasizing consistency of aggregate employment and capital dynamics with hiring and investment decisions at plant level is provided by King and Thomas (2006) and Khan and Thomas (2008), respectively.*

In every period t, the existing capital stock depreciates at the rate δ_K and is augmented by new investment:

$$K_t = (1-\delta_K)K_{t-1} + I_t, \quad 0 < \delta_K < 1. \tag{7}$$

Similarly, the number of a firm's employees decreases at the rate δ_N and it is augmented by new hires H_t. The law of motion for employment reads:

$$N_t = (1-\delta_N)N_{t-1} + H_t, \quad 0 < \delta_N < 1, \tag{8}$$

which implies that new hires are immediately productive.

At the beginning of each period, firms hire new workers and invest in capital. Next, wages are negotiated following standard Nash bargaining. When maximizing its market value, defined as the present discounted value of future cash flows, the representative producer anticipates the impact of its hiring and investment policy on the bargained wage. The intertemporal maximization problem of the firm reads as follows:

$$\max E_t \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left\{ mc_{t+j} \left[f(A_{t+j}, N_{t+j}, K_{t+j-1}) - g(I_{t+j}, K_{t+j-1}, H_{t+j}, N_{t+j}) \right] \right.$$

$$\left. - \frac{W_{t+j}(I_{t+j}, K_{t+j-1}, H_{t+j}, N_{t+j})}{P_{t+j}} N_{t+j} - I_{t+j} \right\},$$

subject to the laws of motion for capital (7) and labor (8), where $\Lambda_{t,t+j} = \beta^j \frac{C_t}{C_{t+j}}$ is the real discount factor of the households who own the firms and $mc_t \equiv P_t^Z / P_t$ is the relative price of the intermediate firm's good. This relative price equals the real marginal cost for a final goods producer since, as discussed later, producers transform one unit of intermediate good into one unit of final good.

The first-order conditions for dynamic optimality are:

$$Q_t^K = E_t \Lambda_{t,t+1} \left[\left(mc_{t+1}(f_{K,t+1} - g_{K,t+1}) - \frac{W_{K,t+1}}{P_{t+1}} N_{t+1} \right) + (1-\delta_K) Q_{t+1}^K \right], \tag{9}$$

$$Q_t^K = mc_t g_{I,t} + \frac{W_{I,t}}{P_t} N_t + 1, \tag{10}$$

$$Q_t^N = mc_t \left(f_{N,t} - g_{N,t} \right) - \frac{W_t}{P_t} - \frac{W_{N,t}}{P_t} N_t + (1-\delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N, \tag{11}$$

$$Q_t^N = mc_t g_{H,t} + \frac{W_{H,t}}{P_t} N_t, \tag{12}$$

where Q_t^K and Q_t^N are the Lagrange multipliers associated with the capital and the employment laws of motion, respectively. One can label Q_t^K as Tobin's Q for capital or the value of capital and Q_t^N as Tobin's Q for labor or the value of labor. For an extensive discussion of their economic significance, see Yashiv (2014).

Substituting for Q_t^K and Q_t^N, the four equations above can be rewritten:

$$mc_t g_{I,t} + \frac{W_{I,t}}{P_t^C} N_t + 1 = E_t \Lambda_{t,t+1} \left\{ mc_{t+1}(f_{K,t+1} - g_{K,t+1}) - \frac{W_{K,t+1}}{P_{t+1}} N_{t+1} \right.$$
$$\left. +(1-\delta_K)(mc_{t+1} g_{I,t+1} + \frac{W_{I,t+1}}{P_{t+1}} N_{t+1} + 1) \right\}, \tag{13}$$

$$mc_t g_{H,t} + \frac{W_{H,t}}{P_t} N_t = mc_t \left(f_{N,t} - g_{N,t} \right) - \frac{W_t}{P_t} - \frac{W_{N,t}}{P_t} N_t$$
$$+(1-\delta_N) E_t \Lambda_{t,t+1} \left(mc_{t+1} g_{H,t+1} + \frac{W_{H,t+1}}{P_{t+1}} N_{t+1} \right), \tag{14}$$

which offer two dynamic equations for the final goods producers' real marginal cost.

In a DSGE model with no frictions and no bargaining, equation (14) implies that the marginal rate of substitution equals the marginal revenue product of employment:

$$W_t / P_t^C = mc_t f_{N,t}$$

while equation (13) implies that the user cost of capital equals the marginal revenue product of capital:

$$E_t R_t / \pi_{t+1} = E_t \left[mc_{t+1} f_{K,t+1} + (1-\delta_K) \right].$$

Final good producers

There is a unit measure of monopolistically competitive final good firms indexed by $i \in [0,1]$. Each firm i transforms $Z(i)$ units of the intermediate good into $Y(i)$ units of a differentiated good, where $Z(i)$ denotes the amount of intermediate input used in the production of good i. Monopolistic competition implies that each final firm i faces the following demand for its own product:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t, \tag{15}$$

where Y_t denotes aggregate demand from the retailers.

We assume price stickiness *à la* Rotemberg (1982), meaning firms maximize current and expected discounted profits subject to quadratic price adjustment costs.

Final good firms maximize the following expression:

$$\max E_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \frac{P_t}{P_{t+s}} \left[\left(P_{t+s}(i) - P_{t+s} mc_{t+s} \right) Y_{t+s}(i) - \frac{\zeta}{2} \left(\frac{P_{t+s}(i)}{P_{t+s-1}(i)} - 1 \right)^2 P_{t+s} Y_{t+s} \right],$$

subject to the demand function (15). The first order conditions with respect to $P_t(i)$ and $Y_t(i)$ read as follows:

$$Y_t(i) - \zeta \left(\frac{P_t(i)}{P_{t-1}(i)} - 1 \right) \frac{1}{P_{t-1}(i)} P_t Y_t = \eta_t \varepsilon \frac{Y_t}{P_t} \left(\frac{P_t(i)}{P_t} \right)^{-\varepsilon - 1}$$
$$-E_t \left[\Lambda_{t,t+1} \frac{P_t}{P_{t+1}} \zeta \left(\frac{P_{t+1}(i)}{P_t(i)^2} \right) \left(\frac{P_{t+1}(i)}{P_t(i)} - 1 \right) P_{t+1} Y_{t+1,} \right] \tag{16}$$

and

$$\eta_t = P_t(i) - P_t \cdot mc_t, \tag{17}$$

where η_t is the Lagrange multiplier associated with eq. (15).

Since all firms set the same price and therefore produce the same output in equilibrium, equations (16) and (17) can be combined to obtain the following law of motion for inflation:

$$\pi_t(1 + \pi_t) = \frac{1 - \varepsilon}{\zeta} + \frac{\varepsilon}{\zeta} mc_t + E_t \frac{1}{1 + r_t} (1 + \pi_{t+1}) \pi_{t+1} \frac{Y_{t+1}}{Y_t}, \tag{18}$$

where we have used $E_t \Lambda_{t,t+1} = \frac{1}{(1+i_t)/(1+\pi_{t+1})} = \frac{1}{1+r_t}$, with i_t and r_t denoting the net nominal and real interest rates, respectively. Equation (18) specifies that inflation depends on marginal costs as well as expected future inflation. Solving forward equation (18), it is possible to show that inflation depends on current and expected future real marginal costs.

2.4 Hiring and Investment Frictions and Marginal Costs

In order to understand the forces driving marginal costs in this model, it is worth solving the FOCs for capital and employment in equations (9) and (11) for mc_t and $E_t mc_{t+1}$, respectively. Rearranging the dynamic optimality condition for employment in (11), we get the following expression:

$$mc_t = \frac{\frac{W_t}{P_t^C}}{f_{N,t} - g_{N,t}} + \frac{\frac{W_{N,t}}{P_t^C} N_t}{f_{N,t} - g_{N,t}} + \frac{Q_t^N - (1 - \delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N}{f_{N,t} - g_{N,t}}. \tag{19}$$

The first term in the above equation is the wage component of marginal costs, expressed as the ratio of real wages to the net marginal product of labor. Because the production function is Cobb-Douglas, in a no friction model, where $g_{N,t} = 0$, the wage component is proportional to the labor share of income $W_t N_t / P_t Y_t$. The second term relates to intra-firm bargaining. Since the marginal product of labor is decreasing with the size of the firm, the marginal worker will decrease the marginal product of labor and the wage bargained by all the intra-marginal workers. Correctly anticipating the effect of hiring policies on the negotiated wage bill generates an incentive to increase hiring. In our model, this intrafirm bargaining effect has an impact on the marginal cost: the marginal cost of expanding output by raising employment, decreases with the negative effect of firm size on the negotiated wage bill.

The third term shows that with frictions in the labor market, marginal costs depend on expected changes in the value of employment, a point already made by Krause, Lopez-Salido and Lubik (2008).

Introducing hiring frictions in a standard New Keynesian model implies that the cost of hiring a marginal worker no longer coincides with the real wage. On top of the wage there are additional costs reflecting the disruption of economic activity that is generated by training new hires for their jobs. Because firms expand employment up to the point where the present value of a marginal hire Q_t^N equals the marginal hiring cost, the term that enters the marginal cost equation in (19) equals the expected change in the marginal hiring cost. So, for instance, an expected increase in marginal hiring costs translates into lower current marginal costs, reflecting the savings of future recruitment costs that can be achieved by recruiting in the current period.

In our model marginal costs are also related to the dynamics of capital. Rearranging equation (9) to solve for expected real marginal cost next period, one gets the following expression:

$$E_t mc_{t+1} = E_t \frac{\frac{W_{K,t+1}}{P_{t+1}} N_{t+1}}{A_{t+1} f_{K,t+1} - g_{K,t+1}} + \frac{1}{\Lambda_{t,t+1}} E_t \frac{Q_t^K - \Lambda_{t,t+1}(1-\delta_K) Q_{t+1}^K}{A_{t+1} f_{K,t+1} - g_{K,t+1}}. \tag{20}$$

The first term in equation (20) is a term reflecting intrafirm bargaining. A higher capital stock makes workers more productive, thereby increasing the expected marginal product of labor and the bargained wage. In equation (9), the presence of this term reflects a typical hold-up problem: because workers appropriate parts of the rents generated by employment, the capital effect on wages decreases the value of capital, leading to under-investment. By rearranging equation (9) to solve for the expected marginal cost, we can look at the effect of capital on wages as a determinant of real marginal costs: the marginal cost of expanding production by increasing capital rises with the positive effect of capital on wages.

The second term shows that expected changes in Tobin's Q for capital (Q^K) also affect real marginal costs: the marginal cost of expanding output by increasing capital is netted out of the expected gains in the value of capital. In analogy with the case of hiring discussed above, the term Q_t^K reflects both the marginal value of a unit of capital and the marginal cost of investment. Hence, the term $Q_t^K - \Lambda_{t,t+1}(1-\delta_K)Q_{t+1}^K$ can be interpreted as the expected change in marginal investment costs, which is always zero in a model with no investment frictions. Friction costs will give rise to richer dynamics in the value of capital, which will be driven, as dictated by equation (10), by changes in marginal investment costs, evaluated in units of forgone output, and by changes in the impact of investment on the negotiated wage bill.

It is worth noting that hiring and investment frictions interact in general equilibrium. Replacing (12) into (10) we get:

$$Q_t^K = \frac{Q_t^N - \frac{W_{H,t}}{P_t^C} N_t}{g_{H,t}} g_{I,t} + \frac{W_{I,t}}{P_t^C} N_t + 1,$$

while substituting (10) into (12) we obtain:

$$Q_t^N = \frac{Q_t^K - \frac{W_{I,t}}{P_t^C} N_t - 1}{g_{I,t}} g_{H,t} + \frac{W_{H,t}}{P_t^C} N_t.$$

Quite clearly, the marginal cost of investing and hiring, which reflect the existence of frictions *as per* equations (10) and (12), directly affect each other.

2.5 Wage Bargaining

Wages are assumed to maximize a geometric average of the household's and the firm's surplus weighted by the parameter γ, which denotes the bargaining power of the households:

$$W_t = \arg\max \left\{ \left(V_t^N\right)^{\gamma} \left(Q_t^N\right)^{1-\gamma} \right\}, \tag{21}$$

The first order condition to this problem leads to the Nash sharing rule:

$$(1-\gamma) V_t^N = \gamma Q_t^N. \tag{22}$$

Substituting (5) and (11) into the above equation and using the sharing rule (22) to eliminate the terms in Q_{t+1}^N and V_{t+1}^N one gets the following expression for the real wage:

$$\frac{W_t}{P_t} = \gamma mc_t \left(f_{N,t} - g_{N,t}\right) - \gamma \frac{W_{N,t}}{P_t} N_t + (1-\gamma) \left[\chi C_t N_{it}^{\varphi} + \frac{x_t}{1-x_t} \frac{\gamma}{1-\gamma} Q_t^N \right]. \tag{23}$$

Assuming a Cobb-Douglas production function and the frictions cost function in (6), the solution to the differential equation in (23) reads as follows:

$$\frac{W_t}{P_t} = mc_t A_t^{\alpha} K_{t-1}^{1-\alpha} \left\{ \alpha \left[1 - \frac{e_1}{\eta_1} \left(\frac{I_t}{K_{t-1}} \right)^{\eta_1} \right] A_1 N_t^{\alpha-1} + \left(1 - \frac{\alpha}{\eta_2}\right) e_2 H_t^{\eta_2} A_2 N_t^{\alpha-1-\eta_2} \right\}$$
$$+ (1-\gamma) \left[\chi C_t N_{it}^{\varphi} + \frac{x_t}{1-x_t} \frac{\gamma}{1-\gamma} \left(mc_t g_{H,t} + \frac{W_{H,t}}{P_t^C} N_t \right) \right], \tag{24}$$

where A_1 and A_2 are parameters, which are reported in the Appendix A together with the full derivation.

Notice that in the special case in which workers have no bargaining power, i.e., $\gamma = 0$, the real wage equals the marginal rate of substitution between consumption and leisure, as in the standard New-Keynesian model with a frictionless labor market.

2.6 Aggregation and Equilibrium Conditions

Aggregating output demand implies the following relationship between consumption and investment demand, and aggregate supply of the final good:

$$C_t + I_t = Y_t = \left(\int_0^1 Y_t(i)^{(\epsilon-1)/\epsilon} di \right)^{\epsilon/(\epsilon-1)} . \tag{25}$$

Aggregating on the supply side of the economy implies the following relationship between final goods and intermediate inputs:

$$Z_t = f(A_t, N_t, K_{t-1}) - g(I_t, K_{t-1}, H_t, N_t) = Y_t \int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} di = Y_t, \tag{26}$$

where $\int_0^1 \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} di = 1$ since with Rotemberg pricing there is no price dispersion in equilibrium.

Combining the expressions in (25) and (26) implies that:

$$C_t + I_t = f(A_t, N_t, K_{t-1}) - g(I_t, K_{t-1}, H_t, N_t). \tag{27}$$

2.7 The Monetary Authority

The monetary authority sets the nominal interest rate following the Taylor rule:

$$\frac{R_t}{R^*} = \left(\frac{R_{t-1}}{R^*} \right)^{\rho_r} \left[\left(\frac{1+\pi_t}{1+\pi^*} \right)^{r_\pi} \left(\frac{Y_t}{Y^*} \right)^{r_y} \right]^{1-\rho_r} \xi_t, \tag{28}$$

where π_t measures the rate of inflation of the numeraire good, and an asterisk superscript denotes the steady-state values of the associated variables. When linearizing the model around the stationary equilibrium we will assume that $\pi^* = 0$. The parameter ρ_r represents interest rate smoothing, and r_y and r_π govern the response of the monetary authority to deviations of output and inflation from their steady-state values. The term ξ_t captures a monetary policy shock, which is assumed to follow the process $ln\xi_t = \rho_\xi ln\xi_{t-1} + e_t^\xi$, with $e_t^\xi \sim N(0, \sigma_\xi)$.

3 Impulse Responses in the Full Model

We start this section by calibrating the full model with price rigidities and with frictions in both labor and capital markets. This will provide a benchmark for the analysis to follow, namely the full DSGE model with all frictions. We then compare how the impulse responses of real variables such as the hiring rate, the investment rate, real wages and net output change when we shut down price frictions and/or frictions in capital and labor markets. In what follows we will look at both technology and monetary shocks.

We linearize the model around the non-stochastic steady state and solve for the policy functions, which express the control variables as a function of the states and the shocks. We then shock the stationary equilibrium of the model with a technological or a monetary innovation, and iterate on the policy functions and on the laws of motion for the state variables to trace the expected behaviour of the endogenous variables, i.e., we produce impulse responses.

3.1 Calibration

We calibrate the parameters that affect the stationary equilibrium of the model using two sources of information: some parameters are either normalized or set using a priori information, while the remaining ones are selected so as to match U.S. data.

Table 1

The discount factor β equals 0.99 implying a quarterly interest rate of 4%. The quarterly job separation rate δ_N is set 0.133 as in the data and measures separations from employment into either unemployment or inactivity (see Appendix B in Yashiv (2014) for details), while the capital depreciation rate δ_K is set to 0.02 to match the US investment to capital ratio. The inverse Frisch elasticity φ is set equal to 3, in line with the range of estimates by Domeji and Floden (2006) and in between the value of 5 used in Gali (2010) and the more standard value of 1 as in Christiano Eichenbaum and Trabant (2013) among many others. The elasticity of substitution in demand ϵ is set to the conventional value of 11, implying a steady-state markup of 10%, consistent with estimates presented in Burnside (1996)and Basu and Fernald (1997). Finally, the scale parameter χ in the utility function is normalized to equal one.

This leaves us with four parameters to calibrate: the elasticity of output to the labor input α, the bargaining power γ and the two scale parameters in the friction costs function, e_1 and e_2. These four parameters are calibrated to match: i) a labor share of 2/3;[4] ii) a ratio of marginal hiring friction costs to the average product of labor, $g_H/(f/N)$, equal to 0.20, which corresponds to nearly one month of wages; iii) a ratio of marginal investment friction costs to the average product of capital, $g_I/(f/K)$, equal to 0.80; iv) total friction costs around 2% of output. Our calibration of costs is conservative in the sense that the target values for total and marginal frictions costs lie at the low part of the spectrum of estimates reported in the literature; we discuss this below. The unemployment rate implied by the calibration is approximately 12%. This value is in line with the average of the time series for unemployment rates produced by the BLS designed to account for

[4] In this model the elasticity of output to the labor income does not correspond exactly to the labor share of income, but these two values are close at the calibrated stationary equilibrium.

workers who are marginally attached to the labor force (U-6), consistently with our measure of the separation rate.[5]

Our calibration of labor frictions merits discussion. The papers of Krause, Lopez-Salido and Lubik (2008) and Gali (2010) assume that average hiring costs equal nearly 5% of quarterly wages, following empirical evidence by Silva and Toledo (2009) on vacancy advertisement costs. Our functional form for friction costs – discussed extensively in Yashiv (2014) – allows for hiring costs to be interpreted in terms of training costs as well as all other sources of forgone output associated with hiring and discussed in Section 2.3. As reported by Silva and Toledo (2009), average training costs are about 55% of quarterly wages, a figure that is nearly ten times as large as that of vacancy posting costs. In our calibration we follow the estimates in Yashiv (2014) and prefer to err on the conservative side: the calibration target for marginal hiring friction costs in point (ii) above implies a ratio of $g_H/(W/P)$ around 30%, nearly one month of wages. Note that the hiring rate H_t/N_t in the data is in the interval $[0.114, 0.161]$ in the period 1976Q1-2011Q4. Hence the ratio of marginal hiring costs over steady state wages $\frac{g_H}{W/P}$, using our calibration values, ranges between 26% and 37% of quarterly wages. This represents relatively little variation and an upper bound that is well below the average training cost reported by Silva and Toledo (2009).[6] The Rotemberg parameter governing price stickiness is set to 120, to match a slope of the Phillips curve of 0.1, as implied by Gali's (2010) calibration.[7] As for the technology shocks, we assume an autocorrelation coefficient $\rho_a = 0.95$, while monetary shocks are assumed to be i.i.d.

3.2 Impulse Responses

Technology Shocks

Figure 1 plots the impulse responses to a positive technology shock in the following four versions of the model: (i) the model with all the frictions – the New-Keynesian model embodying price frictions together with hiring and investment frictions (discussed in the calibration above); (ii) the New Classical model with both capital and labor frictions; this is obtained by setting a very low level of price frictions, i.e. $\zeta \simeq 0$, while maintaining hiring and investment frictions as in the baseline calibration; (iii) the standard New Keynesian model obtained by maintaining a high degree of price rigidities, i.e. $\zeta = 120$, but setting capital and labor frictions close to zero, i.e. $e_1 \simeq 0$ and. $e_2 \simeq 0$; (iv) the standard New Classical model with no frictions obtained by setting $\zeta \simeq 0$, $e_1 \simeq 0$ and $e_2 \simeq 0$.

[5] BLS series can be downloaded at: http://data.bls.gov/pdq/SurveyOutputServlet

[6] The ratio $\frac{g_H}{W/P}$ implied by the functional form in (6) is computed as $e_2\left(\frac{H}{N}\right)\left(\frac{K}{N}\right)^{1-\alpha}/(W/P)$, for different values of H/N assuming $\frac{W}{P}$ and $\frac{K}{N}$ remain constant at their steady state values.

[7] Our value for ζ is obtained by matching the same slope of the Phillips Curve as in Gali: $\frac{\zeta}{\varepsilon} = \frac{(1-\theta_p)(1-\beta\theta_p)}{\theta_p}$, where θ_p is the Calvo parameter. Notice that for given ε and β, this equation implies a unique mapping between θ_p and ζ. While Gali (2010) assumes Calvo pricing frictions, with $\theta_p = 0.75$, we adopt Rotember pricing frictions, which implies that in our specification prices are effectively reset every quarter.

Figure 1

The figure shows that the impulse responses of hiring, employment, investment, capital and output are virtually identical in the two models with hiring and investment frictions (models *i* and *ii* above; the *green* and *blue* lines in the figure); this implies that in the presence of hiring and investment frictions, the response of these real variables is independent of the level of price rigidities.

Upon impact of the technology shock, the response of hiring, employment and output in the standard New-Keynesian benchmark (model iii, the red line) is markedly different with respect to all other models. Employment contracts substantially in this model, which attenuates materially the response of output. Because the job separation rate is very high at quarterly frequencies, the impact of the technology shock on employment is quickly reabsorbed after the first period, implying that the dynamics of the responses beyond the first quarter are broadly similar across models. Interestingly, adding hiring and investment frictions onto the New Keynesian benchmark generates a smoother reaction in real wages, meaning that frictions generate endogenous wage rigidity.

In the New Classical model with no or little frictions (model iv, the black line) the impulse responses are the usual RBC responses with employment, capital and output increasing following a positive technological innovation.

Monetary Shocks

Figure 2 plots impulse responses to an i.i.d. expansionary monetary shock in the same four versions of the model discussed above.

Figure 2

The results show that in the absence of price rigidities, money is neutral, independently of the presence of frictions in labor and capital markets. In the New-Keynesian benchmark (model *iii*) instead, the monetary shock has real effects, but these effects do not last for long, as the model lacks propagation.

Most importantly, real variables respond very differently in the New-Keynesian model with (model *i*) and without (model *iii*) hiring and investment frictions: introducing these frictions virtually eliminates all real effects of monetary shocks, so that the response of the New-Keynesian model with hiring and investment frictions is virtually indistinguishable from the response of the New Classical benchmark. The ineffectiveness of monetary policy to stimulate output is consistent with VAR evidence by Uhlig (2005) who, under agnostic identification assumptions, finds that following a monetary stimulus, output is just as likely to increase as to decrease.

The results above imply that either hiring or investment frictions or their coexistence, neutralize the impact of price frictions on the propagation of technological and monetary shocks. In what follows we elucidate the role of both frictions in the propagation of shocks.

4 Exploring Price Frictions vs. Hiring and Investment Frictions

We aim to study the role of price frictions, such as those underlying New Keynesian models, vs. the role of labor frictions, such as those underlying search models, and capital frictions, such as those underlying Tobin'q investment models. We thus take the New Classical model (NC) as a frictionless benchmark. We then ask what is the effect of introducing price frictions and of introducing labor or capital frictions into the model. We do so by :

(i) Varying the value of the parameter governing price adjustment costs, ζ, and looking at the effect of shocks upon impact on the hiring $(\frac{H_t}{N_t})$ and investment $(\frac{I_t}{K_{t-1}})$ rates, on real wages $(\frac{W_t}{P_t^C})$, and on net output $(f_t - g_t)$. We denote the resulting effect by New Keynesian "NK."

(ii) Varying the value of the parameter governing labor frictions, e_2, and looking at the effect of shocks upon impact on the same variables. We denote the resulting effect by "L frictions."

(iii) Varying the value of the parameter governing capital frictions, e_1, and looking at the effect of shocks upon impact on the same variables. We denote the resulting effect by "K frictions."

(iv) Varying the value of both ζ, and e_1 or e_2 together and looking at the effect of shocks upon impact. We denote the resulting effect by "NK+ L frictions" or "NK+ K frictions."

Using 3D graphs with the relevant parameters variation on two axes and the affected variable on the third axis, we attempt to explain the mechanisms underlying the results.

In the next two sections, we analyze the response of cited variables to technology and to monetary shocks, under these model variations. One aspect of the analysis to note is that we present graphs featuring reasonable ranges of parameter values. The reader can choose a region in the 3D space conforming to his/her own priors to gauge the results. Thus, while we indicate four points in this space, corresponding to the models under review, these are just reference points and the graphs offer a "bigger picture."

In general, before going into the specific analyses, we note the following: price frictions introduce a key role for marginal costs, which serve as a relative price here $mc_t \equiv P_t^Z / P_t^C$; they engender responses of real variables – hiring, investment and the real wage – given the firm's inability to fully and freely adjust prices. Labor (capital) frictions operate to modify the responses of hiring (investment) rates through convex costs functions.

Considering both sets of frictions together, we find that the labor and capital frictions offset price frictions, bringing the total effects closer to the frictionless benchmark. This works in two ways:

(i) The existence of price frictions (the role of mc_t) alters the response of firms' hiring and investment to the value of jobs (Q_t^N) and of capital (Q_t^K).

(ii) Concurrently, the presence of labor and capital frictions affects the response of hiring and investment to changes in the relative price (changes in mc_t).

Note that hiring and investment frictions do not operate trivially by smoothing the response of hiring and investment. The results do not follow from the assumption that frictions in labor and capital markets are large, so quantities cannot respond. Rather, the relative price effect on capital and job values produces non-trivial dynamics, whereby hiring (and investment) increase with labor (and capital) frictions.

These mechanisms generate non-trivial outcomes such as: (*i*) "New Classical outcomes" even with price rigidities; (*ii*) endogenous wage rigidity (by smoothing the response of the marginal rate of substitution between consumption and labor to shocks; (*iii*) much smaller real effects for monetary policy (due to dampening mechanisms). These are not the result of full flexibility but rather of a confluence of frictions.

The following two sections go into the details of these interactions between the two types of frictions.

5 Interactions Between Hiring Frictions and Price Frictions

This section explores the mechanism underlying the interaction between hiring frictions and price frictions. For this purpose we consider a version of the model that restricts investment frictions to be close to zero, i.e., we set $e_1 \simeq 0$, and examine how the impulse responses change on the impact of technology and monetary shocks for different parameterizations of price frictions ζ and hiring frictions e_2. All other parameter values remain fixed at the calibrated values reported in Table 1. We then illustrate the mechanics of the model by referring to key equations.

We plot impulse responses (see figures 4 and 6 below) to technology and monetary shocks for four variables: hiring rates, investment rates, real wages and output. For each variable, we look at how the response on impact changes as we change the parameters governing price frictions, ζ, and hiring frictions, e_2. The area colored in blue (red) denotes the pairs of (ζ, e_2) for which the impulse response is positive (negative). Each point in the figure marks four benchmark calibrations: the New Keynesian benchmark with hiring frictions, featuring high price frictions and moderate hiring frictions, i.e. $\zeta = 120$ and $e_2 = 1.5$; the New Classical benchmark with hiring frictions, featuring *no* price frictions, $\zeta \simeq 0$, and moderate hiring frictions, $e_2 = 1.5$, implying that marginal hiring costs are equivalent to about one month of wages; the New-Keynesian benchmark, featuring high price frictions and *no* hiring frictions, i.e. $\zeta = 120$ and $e_2 \simeq 0$; and the New Classical benchmark, obtained by restricting price and hiring frictions to values *close to zero*, i.e. $\zeta \simeq 0$ and $e_2 \simeq 0$. In the figures, colored points are used to emphasize these four benchmark parameterizations.

To understand the transmission of both technology and monetary shocks in the presence of hiring frictions only, it is crucial to understand what drives the hiring decision. For this purpose it is useful to rewrite equation (12), solving for the effective job value expressed in units of intermediate goods:

$$\frac{\widetilde{Q_t^N}}{mc_t} = g_{H,t} \tag{29}$$

where

$$\widetilde{Q_t^N} \equiv Q_t^N - \frac{W_{H,t}}{P_t^C} N_t,$$
$$= mc_t \left(f_{N,t} - g_{N,t}\right) - \frac{W_t}{P_t} - \frac{W_{N,t}}{P_t} N_t + (1-\delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N - \frac{W_{H,t}}{P_t} N_t,$$

and the last equality follows by replacing Q_t^N using equation (11). Substituting this expression for $\widetilde{Q_t^N}$ into (29) we get:

$$\frac{mc_t \left(f_{N,t} - g_{N,t}\right) - \frac{W_t}{P_t} - \frac{W_{N,t}}{P_t} N_t - \frac{W_{H,t}}{P_t} N_t + (1-\delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N}{mc_t} = g_{H,t}. \tag{30}$$

The LHS are current flow profits $\left(mc_t \left(f_{N,t} - g_{N,t}\right) - \frac{W_t}{P_t} - \frac{W_{N,t}}{P_t} N_t - \frac{W_{H,t}}{P_t} N_t\right)$ and the expected present value of future profits $\left((1-\delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N\right)$. These are divided by the relative price mc_t. The RHS are marginal hiring friction costs. Note that because the marginal hiring cost on the RHS is linearly increasing in the hiring rate, an increase or decrease in the LHS will translate into a similar response in the hiring rate. We shall use this representation in what follows.

5.1 Effects of Technology Shocks

Before we turn to the analysis of the four specific cases discussed above, it is worth looking at how the response of marginal costs on impact changes with price and hiring frictions (Figure 3).

Figure 3

With a positive technology shock marginal costs $mc_t = \frac{P_t^Z}{P_t^C}$ fall as the net marginal product of labor increases (see equation 19). Only in the special case where prices are fully flexible relative prices don't move. The higher are price frictions the stronger is the fall in marginal costs, while labor frictions have a negligible impact. The role of price frictions is thus expressed strongly through changes in the marginal costs, which are relative prices.

Figure 4

The New Classical Benchmark

The effective job value (LHS of equation (30)) goes up because mc_t does not change, and $\widetilde{Q_t^N}$ (the numerator) goes up, driven by higher current and future $f_{N,t}$. Hence the hiring rate goes up. The response of the investment rate is positive as $f_{K,t+1}$ rises with little changes in other variables in equation (9). Output rises as productivity and employment rise and finally, real wages go up as the marginal product of labor, $f_{N,t}$, and the marginal rate of substitution, $\chi_t C_t N_t^{\varphi}$, go up (see equation 23).

The New Classical Model with Labor Frictions

This is a very similar case to the preceding one, but higher labor frictions now generate a slightly weaker response of hiring. Employment increases by less, dampening the response of real wages via the marginal rate of substitution $\chi_t C_t N_t^{\varphi}$, and the response of investment via the marginal product of capital, due to complementarities in the production function. A slightly smaller increase in hiring and employment implies that also output increase a little less. The lower rise in investment does not contribute to the explanation why output rises by less on impact since output depends only on the previous period stock of capital.

The New Keynesian Benchmark

The effect of technological shocks on hiring is the result of two contradictory forces: the direct (positive) effect of A_t on productivity and the present value of the job $\widetilde{Q_t^N}$, and the indirect (negative) effect that goes through the response of marginal costs. It turns out that the latter dominates and hiring declines.

To understand the partial effect of technology on hiring that goes through the endogenous response of marginal costs, it is worth focusing on the product of the elasticities: the total elasticity of marginal costs with respect to technology shocks η_{mc_t,e_t^a}, and the partial elasticity of the hiring rate with respect to marginal costs $\eta_{\frac{H_t}{N_t},mc_t}$. Because the former is virtually independent of e_2 (see Figure 3), we can get the intuition for the result by focusing on the latter.

Substituting for $g_{H,t}$ using the functional form in equation (6), we can rewrite equation (30) as follows:

$$\frac{H_t}{N_t} = \frac{mc_t B_t - C_t}{mc_t} \frac{1}{e_2 A_t \left(K_{t-1}/N_t\right)^{1-\alpha}},$$

where $B_t \equiv f_{N,t} - g_{N,t}$ and $C_t \equiv \frac{W_t}{P_t} + \frac{W_{N,t}}{P_t} N_t - (1-\delta_N) E_t \Lambda_{t,t+1} Q_{t+1}^N + \frac{W_{H,t}}{P_t} N_t$. We can then use the above equation to work out the partial derivative of hiring rates with respect to marginal costs,

$$\frac{\partial \frac{H_t}{N_t}}{\partial mc_t} = \frac{mc_t \left(f_{N,t} - g_{N,t}\right) - \widetilde{Q_t^N}}{mc_t^2} \frac{1}{e_2 A_t \left(K_{t-1}/N_t\right)^{1-\alpha}}, \tag{31}$$

where we have used $\widetilde{Q_t^N} \equiv mc_t B_t - C_t$. Note that the associated elasticity is $\eta_{\frac{H_t}{N_t},mc_t} = \frac{\partial \frac{H_t}{N_t}}{\partial mc_t} \cdot \frac{mc_t}{\frac{H_t}{N_t}}$.

Because the value of a job, $\widetilde{Q_t^N}$ approaches zero as labor frictions decrease, i.e. as $e_2 \to 0$, and because $f_{N,t} - g_{N,t} > 0$, the elasticity $\eta_{\frac{H_t}{N_t},mc_t}$ is positive. Given that marginal costs fall with positive technology shocks, the partial effect of technology on hiring that goes through marginal cost is negative. This is the standard mechanism at work in New Keynesian models: because output is demand driven with price rigidities, an increase in productivity implies that less input is needed to meet demand, so employment must fall. The fall in hiring needed to meet demand is proportional to the marginal revenue product. When $e_2 \simeq 0$ this effect is stronger than the direct effect of technology on the marginal product of labor, which tends to increase the present value of the job. Hence the response of both hiring and employment is negative.

We now turn to discuss the response of the other real variables reported in Figure 4. Real wages go down as mc_t and $\chi_t C_t N_t^{\varphi}$ fall; investment rises, but by much less as employment falls, so by the complementarities in the production function the marginal product of capital increases by less; output rises but not by much as in the New Classical benchmark because hiring (and therefore employment) falls.

New Keynesian model with labor frictions and price frictions

As hiring frictions increase, the rent associated with a filled job increases, hence $\widetilde{Q_t^N}$ in equation (31) rises, decreasing the elasticity of hiring to marginal costs $\eta_{\frac{H_t}{N_t},mc_t}$. This effect derives from interacting price and hiring frictions, and reflects the impact of relative prices (mc_t) on the value of a job in units of intermediate goods (the LHS of (29)). Whether this effect will be sufficient to overturn the sign of the response of hiring is a numerical question. It turns out that at the calibrated equilibrium, for parameterizations of labor market frictions that reflect conservative estimates of training costs, the response of hiring turns positive on the impact of technology shocks.

The increase in employment implies that wages fall by less than in the New Keynesian model with a frictionless labor market; the effect of employment on the marginal rate of substitution endogenously dampens the reaction of real wages. It is also worth noting that for values of ζ around 60, which map into a Calvo price stickiness of $2 - 2\frac{1}{2}$quarters,[8] increasing e_2 can turn the response of real wages to technology shocks from negative to positive, that is, it reproduces the qualitative response that we observe in a New Classical benchmark. Investment rises substantially; as hiring rates increase with higher labor market frictions e_2, the marginal productivity of capital rises. Finally output rises substantially as productivity and employment rise.

In summary, as Figure 4 shows, adding labor (hiring) frictions to price frictions brings the New Keynesian model closer to the results of the New Classical model with labor frictions, i.e., offsets to a significant extent the effects of price frictions.

5.2 Effects of Monetary Shocks

With a monetary expansion $mc_t = \frac{P_t^Z}{P_t^C}$ rises as the labor share increases. The mechanism is as follows: a fall in the nominal rate engenders a fall in the real rate that stimulates consumption and investment. In order to meet the increase in output demand, the demand for labor rises, so the real wage increases, and in turn this increases the real marginal costs through the rise in labor share.

Before we start discussing the four benchmark cases it is worth inspecting how the impact elasticity of marginal costs to monetary shocks changes with price frictions and hiring frictions.

Figure 5

Figure 5 shows that only in the special case where prices are fully flexible marginal costs do not respond. The response of marginal costs increases with price frictions ζ and is virtually independent

[8]See footnote 6.

of hiring frictions e_2.

Figure 6

The New Classical Benchmark

The present value of the job does not change as basically nothing moves in the hiring equation (30). Likewise, real wages, investment and output do not change. This is an expression of money neutrality.

The New Classical Model with Labor Frictions

Because marginal costs do not respond to monetary shocks, money is still neutral.

The New-Keynesian Benchmark

The effective job value rises and the effect on hiring rates is quantitatively substantial. This is so as marginal costs respond to monetary shocks and the elasticity of hiring rates to marginal costs $\eta_{\frac{H_t}{N_t},mc_t}$ is positive when employment relationships generate no rent (the numerator in the RHS of equation (31) is positive as $\widetilde{Q_t^N}$ approaches zero for $e_2 \rightarrow 0$). The response of the other real variables follows: real wages rise as mc_t and $\chi_t C_t N_{it}^{\varphi}$ rise; the response of the investment rate is positive as the marginal cost rises and the marginal product of capital increases with employment; output rises when hiring rates and employment rise.

The New-Keynesian Model with Labor Frictions

As e_2 rises, the value of a job $\widetilde{Q_t^N}$ increases and the elasticity of hiring to marginal costs $\eta_{\frac{H_t}{N_t},mc_t}$ falls (see equation (31)). At the calibrated equilibrium, for reasonable parameterizations of hiring frictions, the elasticity of hiring rates to marginal costs switches from positive to negative, implying that monetary stimuli could even be contractionary. Under the assumption of hiring frictions equal to roughly one month of wages, hiring is neutral, i.e., does not respond to monetary policy. Note that this is not the result of flexibility but rather of a confluence of frictions. As a consequence, the real wage response is muted relative to the benchmark New Keynesian model, as the marginal rate of substitution does not respond as much. Thus labor frictions generate endogenous real wage rigidity by containing movements in the marginal rate of substitution. Because employment does not respond with moderate hiring frictions, the productivity of capital remains unchanged, hence investment does not respond. Output also remains unchanged and money is neutral.

Typically, as noted above, New Keynesian models with search frictions calibrate hiring frictions to match vacancy posting costs (see Krause, Lopez-Salido and Lubik (2008) and Gali (2010)). These costs are very small, equivalent to about one week of wages.

Figure 6 recovers Gali's (2010) result that the performance of the New Keynesian model is virtually independent of hiring frictions, but this conclusion holds true only in the special case where the labor market is nearly frictionless. Importantly, what Figure 6 also shows is that for tiny parameterizations of hiring frictions, the elasticity of hiring rates to marginal costs is very sensitive to the precise level of frictions. Calibrating hiring frictions to match training costs, which are an order of magnitude higher than vacancy posting costs, would imply selecting values for e_2 that are larger than 1.5. In this region of the parameter space, a monetary stimulus reduces both employment and capital as well as output. As a result, marginal costs, conditional on monetary shocks, become countercyclical, in line with empirical evidence by Nekarda and Ramey (2013), and in contrast to the predictions of the baseline New Keynesian model with a frictionless, or nearly frictionless, labor market.

6 Interactions Between Investment Frictions and Price Frictions

This section explores the mechanism underlying the interaction between investment frictions and price frictions. For this purpose we consider a version of the model that restricts hiring frictions to be close to zero, i.e. we set $e_2 \simeq 0$, and examine how the impulse responses change on the impact of technology and monetary shocks for different parameterizations of price frictions ζ and investment frictions e_1. All other parameter values remain fixed at the calibrated values reported in Table 1.

In Figures 8 and 10 we plot impulse responses to technology and monetary shocks for the same four variables as before, marking again the same four benchmark parameterizations: the New Keynesian benchmark with investment frictions, featuring high price frictions and moderate investment frictions, i.e. $\zeta = 120$ and $e_1 = 40$; the New Classical benchmark with investment frictions, featuring no price frictions, $\zeta \simeq 0$, and moderate investment frictions, $e_1 = 40$, implying the same ratio of marginal investment costs to the marginal product of capital as in the calibration discussed in Section 3.1; the New-Keynesian benchmark, featuring high price frictions and no investment frictions, i.e. $\zeta = 120$ and $e_1 \simeq 0$; and the New Classical benchmark, obtained by setting investment and price frictions close to zero, i.e., $\zeta \simeq 0$ and $e_1 \simeq 0$.

To understand the investment decision, rearrange equation (10) to solve for the relevant capital value expressed in units of intermediate goods

$$\frac{\widetilde{Q_t^K}}{mc_t} = g_{I,t}, \tag{32}$$

where $\widetilde{Q_t^K}$ can be expressed as follows by making use of equation (9):

$$\begin{aligned}\widetilde{Q_t^K} &= Q_t^K - \frac{W_{I,t}}{P_t} N_t - 1 \\ &= E_t \Lambda_{t,t+1} \left[\left(mc_{t+1}(f_{K,t+1} - g_{K,t+1}) - \frac{W_{K,t+1}}{P_{t+1}} N_{t+1} \right) + (1-\delta_K) Q_{t+1}^K \right] - \frac{W_{I,t}}{P_t} N_t - 1.\end{aligned}$$

Replacing the above expression into equation (32) yields:

$$\frac{E_t\Lambda_{t,t+1}\left[\left(mc_{t+1}(f_{K,t+1}-g_{K,t+1})-\frac{W_{K,t+1}}{P_{t+1}}N_{t+1}\right)+(1-\delta_K)Q^K_{t+1}\right]-\frac{W_{I,t}}{P^C_t}N_t-1}{mc_t}=g_{I,t}. \tag{33}$$

We shall use this equation in what follows.

6.1 Effects of Technology Shocks

Figure 7 shows that the total elasticity of marginal cost to technology shocks η_{mc_t,e^a_t} is negative and increasing (in absolute value) with price frictions ζ. Only in the special case where prices are fully flexible does the marginal cost not respond. Also, for relatively high values of price rigidities, investment frictions reduce the elasticity of marginal cost.

The New Classical Benchmark

The present value of investment (LHS of equation (33)) goes up because marginal costs are unaffected, and $\widetilde{Q^K_t}$ (the numerator) goes up, due to higher current and future $f_{K,t}$. Hence a positive technology shock, raises investment: the RHS of equation (33), $g_{I,t}$, increases linearly with $\frac{I_t}{K_t}$ The response of the hiring rate is positive as $f_{N,t+1}$ rises with the technology neutral shock. Real wages go up as $f_{N,t}$ and $\chi_t C_t N^{\varphi}_{it}$ (the MRS term) go up. Output rises as hiring rates and employment rise.

The New Classical Model with Capital Frictions

Basically this case is similar to the preceding one with some mitigation of the investment response due to frictions.

The New Keynesian Benchmark

The response of the investment rate depends on two contradictory forces: the direct (positive) impact of technology that goes through the marginal product of capital, as described above, and the indirect (negative) effect that goes through the response of marginal costs. To understand this second effect, it is convenient to solve equation (33) for the investment rate, after replacing $g_{I,t}$ with the functional form given by equation (6):

$$\frac{I_t}{K_{t-1}}=\frac{E_t\Lambda_{t,t+1}\left[\left(mc_{t+1}(f_{K,t+1}-g_{K,t+1})-\frac{W_{K,t+1}}{P_{t+1}}N_{t+1}\right)+(1-\delta_K)Q^K_{t+1}\right]-\frac{W_{I,t}}{P_t}N_t-1}{mc_t}\frac{1}{e_1A_tN^{\alpha}_tK^{-\alpha}_{t-1}}$$

The mechanism by which shocks affect investment rates via the response of marginal costs can be broken down into (i) the effect of investment rates on the change in current marginal costs mc_t; and (ii) the response of investment rates to expected marginal costs next period, E_tmc_{t+1}:

$$\frac{\partial\frac{I_t}{K_{t-1}}}{\partial E_tmc_{t+1}}=\frac{E_t\Lambda_{t,t+1}(f_{K,t+1}-g_{K,t+1})}{mc^2}\frac{1}{e_1A_tN^{\alpha}_tK^{-\alpha}_{t-1}}>0 \tag{34}$$

$$\frac{\partial \frac{I_t}{K_{t-1}}}{\partial mc_t} = \frac{-\widetilde{Q_t^K}}{mc^2} \frac{1}{e_1 A_t N_t^{\alpha} K_{t-1}^{-\alpha}}, \tag{35}$$

The expression in equation (34) captures the standard mechanism at work in New Keynesian models: because output is demand driven when prices are sticky, lower levels of factors of production are required to meet the demand, hence investment rates fall with (future expected) marginal costs.

The expression in equation (35), instead captures the interaction of investment frictions with price frictions. Note that it is zero when $e_1 \simeq 0$ and thus $\widetilde{Q_t^K} \simeq 0$, for the current case.

Coming back to the two effects together, when $e_1 \simeq 0$ the direct impact of technology on investment through the marginal product of capital is quantitatively stronger than the indirect effect that goes through the response of marginal costs. As a result, investment increases.

The response of the hiring rate is negative because with the labor market being frictionless, the numerator in equation (31) is positive, so hiring rates and marginal costs move in the same direction. Finally, real wages go down as mc_t and $\chi_t C_t N_{it}^{\varphi}$ fall and output rises but not by much as hiring (and therefore employment) falls.

The New Keynesian Model with Capital Frictions

Investment rises, as in the New Keynesian baseline case just described, driven by the increase in the marginal product of capital. Indeed, investment rises by more, relative to the New Keynesian model with frictionless capital markets, because higher investment frictions (a higher $\widetilde{Q_t^K}$) offset the negative impact of technology on investment that goes through (next period) marginal costs (compare equations 34 and 35); this is a relative price effect on the value of capital produced by the interaction between price and investment frictions. So this mechanism tends to offset the baseline mechanism at work in New-Keynesian models.

The effective present value of the job declines, just as in the baseline New Keynesian case, so the hiring rate falls. However, the fall is less marked because investment rates rise by more, which increases $f_{N,t}$. Finally, real wages decline; frictions make the response of employment muted; in this case employment decreases by less than in the New Keynesian model with frictionless capital markets, hence real wages fall by less (through the MRS term). Output rises, as in the New Keynesian model with a frictionless capital market, but by more, as the fall in hiring and hence employment is less pronounced.

To sum up, the qualitative response of the four real variables above is the same in the New Keynesian model with and without investment frictions. Quantitatively, the responses in the New Keynesian model get closer to the ones in the New Classical benchmark as investment frictions rise, but only by a limited amount.

6.2 Effects of Monetary Shocks

The New Classical Benchmark with or without Capital Frictions: the marginal cost does not respond, so money is neutral.

The New Keynesian Benchmark: Marginal costs increase with price frictions. The effective present value of the job and capital value rise, and the effect on both hiring rates and investment rates is positive and quantitatively substantial. This is so as the elasticity of both hiring rates and investment rates to marginal costs is positive and strong when employment and capital generate no rent. Real wages increase as both the marginal cost and the marginal rate of substitution increase. Output increases reflecting the increase in hiring and employment.

The New Keynesian Model with Capital Frictions: Investment frictions decrease the elasticity of investment rates to marginal costs $\eta_{\frac{I_t}{K_{t-1}},mc_t}$ (see equation (35)), so investment increases by less. As a result the value of the job increases by less, implying lower hiring and employment relative to the case without investment frictions. A relatively lower level of employment implies a relatively lower increase in the marginal rate of substitution and in real wages. For the same reason, also output increases by less.

To sum up, investment frictions reduce the effectiveness of a monetary stimulus, but not enough to make it totally ineffective or to reverse the impact it has in the frictionless benchmark.

7 Conclusions

We have shown that the transmission mechanism of technology and monetary shocks in DSGE models critically hinges upon hiring frictions and, to a lesser extent, on investment frictions. Most of the empirical research in this field has focused on measuring price rigidities, under the common belief that this is a necessary statistic to gauge the strength of the New-Keynesian mechanism. Our results indicate that if hiring frictions are strong enough, the precise degree of price rigidity is less relevant, if not irrelevant, in the propagation of shocks. Therefore, a correct assessment of hiring costs is key in the calibration of DSGE models.

This paper suggests that for reasonable parameterizations of the model, expansionary monetary policy is neutral if not contractionary. This raises the question whether the mechanism at work in New Keynesian models is not effective, and possibly money matters through other channels or refinements of the baseline mechanism, or whether money is in fact neutral and, as Uhlig (2005) posits, identifying assumptions on VARs are selected so as to confirm our priors on the effectiveness of monetary stimuli.

The focus of this paper is on understanding how hiring and investment frictions affect the propagation of shocks to real variables in DSGE models with price rigidities. The next obvious question to address is what are the implications of these frictions for inflation dynamics. We tackle this issue in separate work, where we also take the model to the data and carry out model comparisons to see what specification of the model is most likely to have produced the data, given a common set of priors on parameter values.

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Appendix A
Solving for the Wage with Intrafirm Bargaining

We rewrite below for convenience the wage sharing rule consistent with Nash bargaining as derived in equation (22):

$$(1-\gamma)V_{it}^{N} = \frac{\gamma Q_{jt}^{N}}{1-\tau}, \tag{36}$$

where we make use of subscripts i and j to denote a particular household i and firm j bargaining over the wage W_{jt}.

Substituting (5) and (11) into the above equation one gets:

$$\gamma \left\{ \left[mc_{jt}\left(f_{N,jt} - g_{N,jt}\right) - \frac{W_{jt}}{P_t} - \frac{W_{N,jt}}{P_t} N_{jt} \right] + \beta(1-\delta_N) E_t \frac{C_t}{C_{t+1}} \frac{Q_{jt+1}^{N}}{1-\tau} \right\} =$$

$$(1-\gamma) \left[\frac{W_{jt}}{P_t} - \chi N_{it}^{\varphi} C_t - \frac{x_t}{1-x_t} V_t^N + \beta\left(1-\delta_N\right) E_t \frac{C_t}{C_{t+1}} V_{it+1}^{N} \right].$$

Using the sharing rule in (36) to cancel out the terms in Q_{jt+1}^{N} and V_{it+1}^{N} we obtain the following expression for the real wage:

$$\frac{W_{jt}}{P_t} = \gamma mc_{jt}\left(f_{N,jt} - g_{N,jt}\right) - \gamma \frac{W_{N,jt}}{P_t} N_{jt} + (1-\gamma)\left[\chi C_t N_{it}^{\varphi} + \frac{x_t}{1-x_t} \frac{\gamma}{1-\gamma} \frac{Q_t^N}{1-\tau} \right]. \tag{37}$$

Ignoring the term in square brackets, which is independent of N_{jt}, and dropping all subscripts from now onward with no risk of ambiguity, we can rewrite the above equation as follows:

$$W_N + \frac{1}{\gamma N} W - Pmc\left(\frac{f_N}{N} - \frac{g_N}{N}\right) = 0 \tag{38}$$

The solution of the homogeneous equation:

$$W_N + \frac{1}{\gamma N} W = 0, \tag{39}$$

is

$$W(N) = CN^{-\frac{1}{\gamma}}, \tag{40}$$

where C is a constant of integration of the homogeneous equation. Assuming that C is a function of N and deriving (40) w.r.t. N, yields:

$$W_N = C_N N^{-\frac{1}{\gamma}} - \frac{1}{\gamma} C N^{-1-\frac{1}{\gamma}}. \tag{41}$$

Substituting (40) and (41) into (38) one gets:

$$C_N = N^{\frac{1-\gamma}{\gamma}} Pmc(f_N - g_N). \tag{42}$$

Integrating (42) yields:

$$C = Pmc\int_0^N z^{\frac{1-\gamma}{\gamma}}(f_z - g_z)dz + D, \tag{43}$$

where D is a constant of integration. Let's solve for the two integrals in f_z and g_z, one at a time. Assuming that $f(Az, K) = (Az)^{\alpha} K^{1-\alpha}$, we can write:

$$Pmc\int_0^N z^{\frac{1-\gamma}{\gamma}} f_z dz = Pmc\alpha\frac{\gamma}{1-\gamma(1-\alpha)} A^{\alpha} N^{\frac{1-\gamma(1-\alpha)}{\gamma}} K^{1-\alpha}. \tag{44}$$

Given our assumptions on the functional form of g as in (6), the function g_N can be rearranged as follows:

$$g_N = -A^{\alpha}K^{1-\alpha}e_2H^{\eta_2}N^{\alpha-1-\eta_2} + \alpha A^{\alpha}K^{1-\alpha}\left[\frac{e_1}{\eta_1}\left(\frac{I}{K}\right)^{\eta_1} N^{\alpha-1} + \frac{e_2}{\eta_2}H^{\eta_2}N^{\alpha-1-\eta_2}\right] \tag{45}$$

Integrating separately the two additive terms in the first row of the above equation yields:

$$Pmc\int_0^N z^{\frac{1-\gamma}{\gamma}} A^{\alpha}K^{1-\alpha}e_2H^{\eta_2}z^{\alpha-1-\eta_2}dz = Pmce_2H^{\eta_2}A^{\alpha}K^{1-\alpha}\frac{\gamma}{1-\gamma+\gamma(\alpha-\eta_2)}N^{\frac{1-\gamma+\gamma(\alpha-\eta_2)}{\gamma}}, \tag{46}$$

Integrating separately the three terms on the second row of equation (45) yields:

$$-Pmc\int_0^N z^{\frac{1-\gamma}{\gamma}} \alpha A^{\alpha}K^{1-\alpha}\frac{e_1}{\eta_1}\left(\frac{I}{K}\right)^{\eta_1} z^{\alpha-1}dz = -Pmc\frac{e_1}{\eta_1}\left(\frac{I}{K}\right)^{\eta_1}\alpha A^{\alpha}K^{1-\alpha}\frac{\gamma}{1-\gamma(1-\alpha)}N^{\frac{1-\gamma(1-\alpha)}{\gamma}}, \tag{47}$$

$$-Pmc\int_0^N z^{\frac{1-\gamma}{\gamma}} \alpha A^{\alpha}K^{1-\alpha}\frac{e_2}{\eta_2}H^{\eta_2}z^{\alpha-1-\eta_2}dz = -Pmc\frac{e_2}{\eta_2}H^{\eta_2}\alpha A^{\alpha}K^{1-\alpha}\frac{\gamma}{1-\gamma+\gamma(\alpha-\eta_2)}N^{\frac{1-\gamma+\gamma(\alpha-\eta_2)}{\gamma}}, \tag{48}$$

Denoting $A_1 \equiv \frac{\gamma}{1-\gamma(1-\alpha)}$ and $A_2 \equiv \frac{\gamma}{1-\gamma+\gamma(\alpha-\eta_2)}$, we can now rewrite (43) as follows:

$$C = D + P^C mcA^{\alpha}K^{1-\alpha}\alpha\left\{A_1N^{1/A_1} + e_2H^{\eta_2}A_2N^{1/A_2} - \alpha\frac{e_1}{\eta_1}\left(\frac{I}{K}\right)^{\eta_1}A_1N^{1/A_1} - \alpha\frac{e_2}{\eta_2}H^{\eta_2}A_2N^{1/A_2}\right\}. \tag{49}$$

Plugging (49) into (40) one gets:

$$W(N) = DN^{-\frac{1}{\gamma}} + PmcA^{\alpha}K^{1-\alpha}\left\{\alpha\left[1-\frac{e_1}{\eta_1}\left(\frac{I}{K}\right)^{\eta_1}\right]A_1N^{\alpha-1} + \left(1-\frac{\alpha}{\eta_2}\right)e_2H^{\eta_2}A_2N^{\alpha-1-\eta_2}\right\}. \tag{50}$$

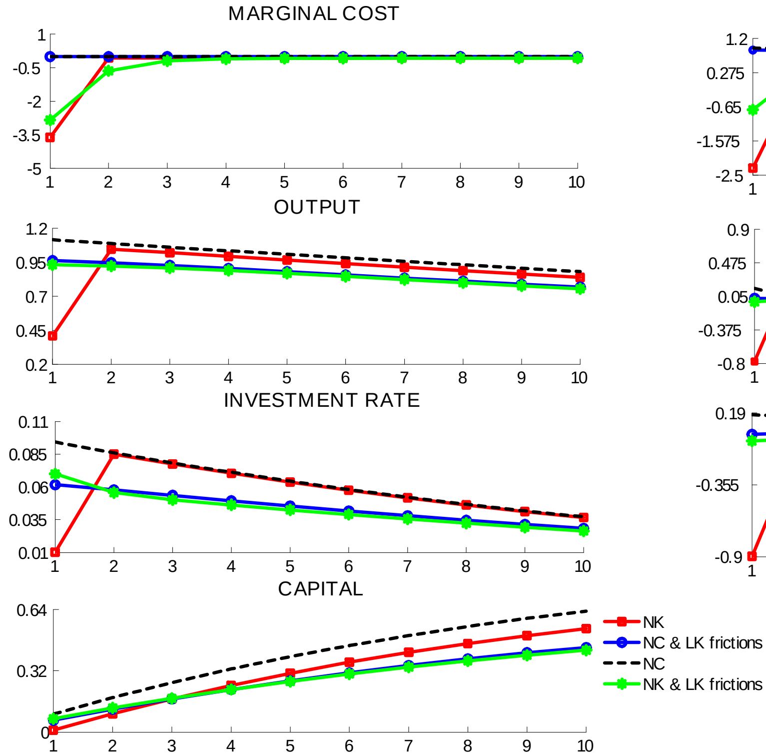
In order to eliminate the constant of integration D we assume that $\lim_{N\to 0} NW(N) = 0$. The solution to (37) therefore is:

$$\begin{aligned}\frac{W_t}{P_t} &= \gamma mc_t A_t^{\alpha}K_{t-1}^{1-\alpha}\left\{\alpha\left[1-\frac{e_1}{\eta_1}\left(\frac{I_t}{K_{t-1}}\right)^{\eta_1}\right]A_1N_t^{\alpha-1} + \left(1-\frac{\alpha}{\eta_2}\right)e_2H_t^{\eta_2}A_2N_t^{\alpha-1-\eta_2}\right\}\\ &\quad + (1-\gamma)\left[\chi C_t N_t^{\varphi} + \frac{x_t}{1-x_t}\frac{\gamma}{1-\gamma}\left(mc_t g_{H,t} + \frac{W_{H,t}}{P_t}N_t\right)\right].\end{aligned} \tag{51}$$

Table 1: IR Analysis: Calibrated Parameters and Steady State Values

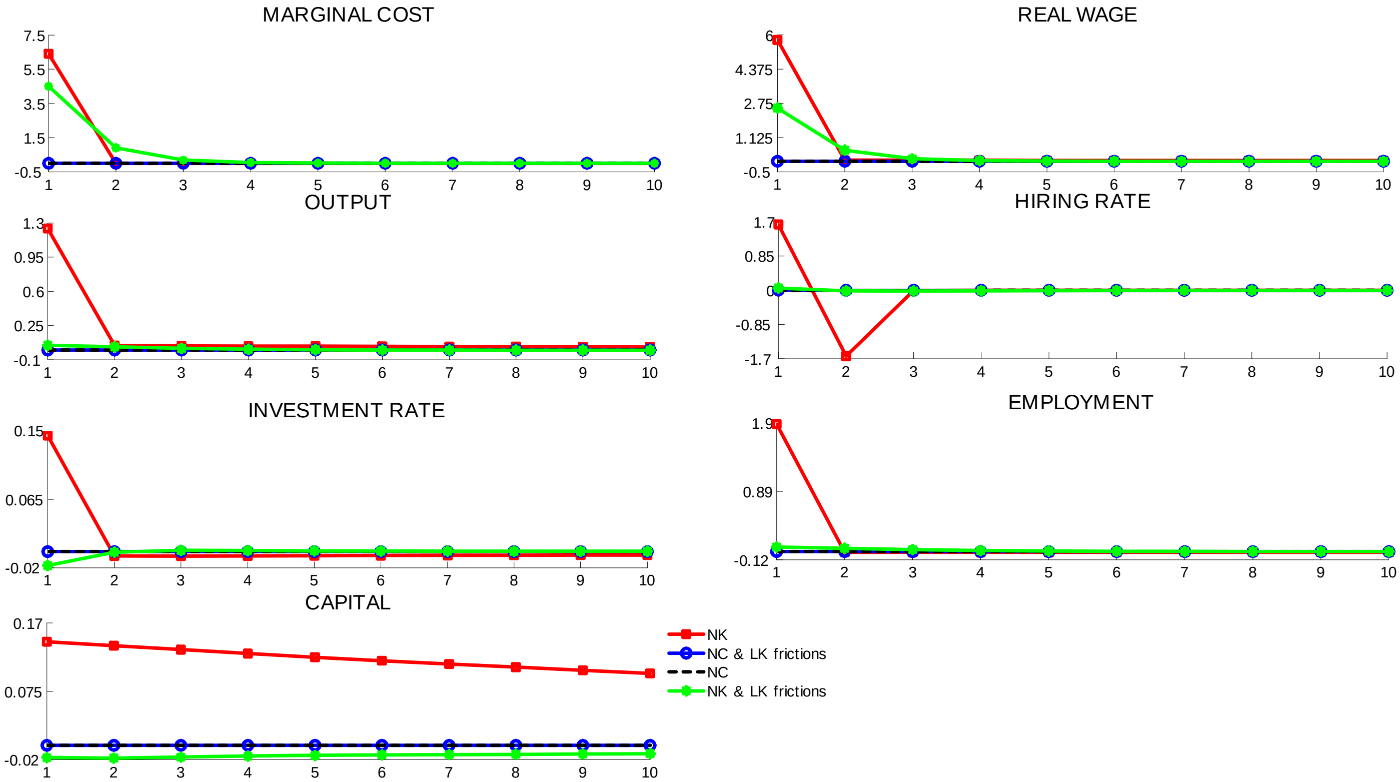
Description	*Parameter*	*Value*
Discount factor	β	0.99
Separation rate	δ_N	0.133
Capital depreciation rate	δ_K	0.02
Elasticity of output to labor input	α	0.66
Investment frictions	e_1	40
Hiring frictions	e_2	1.5
Elasticity of substitution	ϵ	11
Workers' bargaining power	γ	0.28
Scale parameter in utility function	χ	1
Inverse Frisch elasticity	φ	3
Price frictions (Rotemberg)	ζ	120
Taylor rule coefficient on inflation	r_π	1.5
Taylor rule coefficient on output	r_y	0.125
Taylor rule smoothing parameter	ρ_r	0.75
Autocorrelation technology shock	ρ_a	0.95
Autocorrelation monetary shock	ρ_ξ	0
Panel B: Steady State Values		
Definition	*Expression*	*Value*
Total adjustment cost/ output	g_t/y_t	0.02
Marginal investment cost	$g_{I,t}/(y_t/k_t)$	0.8
Marginal hiring cost	$g_{H,t}/(y_t/n_t)$	0.20
Labor share of income	$\frac{(w/p)}{[(F-g)/n]}$	2/3
Unemployment rate	u_t	0.12

Figure 1: Impulse responses to a technology shock



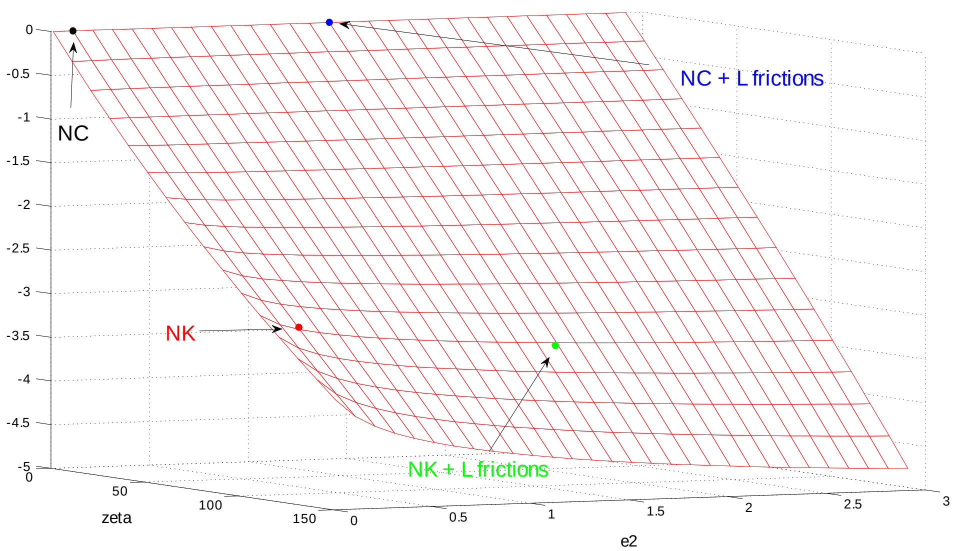
Notes: The figure shows impulse responses to a one percent technology shock obtained in four benchmark parameterizations of the model: 1) the New Classical model (NC); 2) the New Classical model with labor and capital frictions (NC & LK frictions); 3) the New-Keynesian model (New Keynesian); 4) the New-Keynesian model with labor and capital frictions (New Keynesian and LK frictions).

Figure 2: Impulse responses to a monetary shock



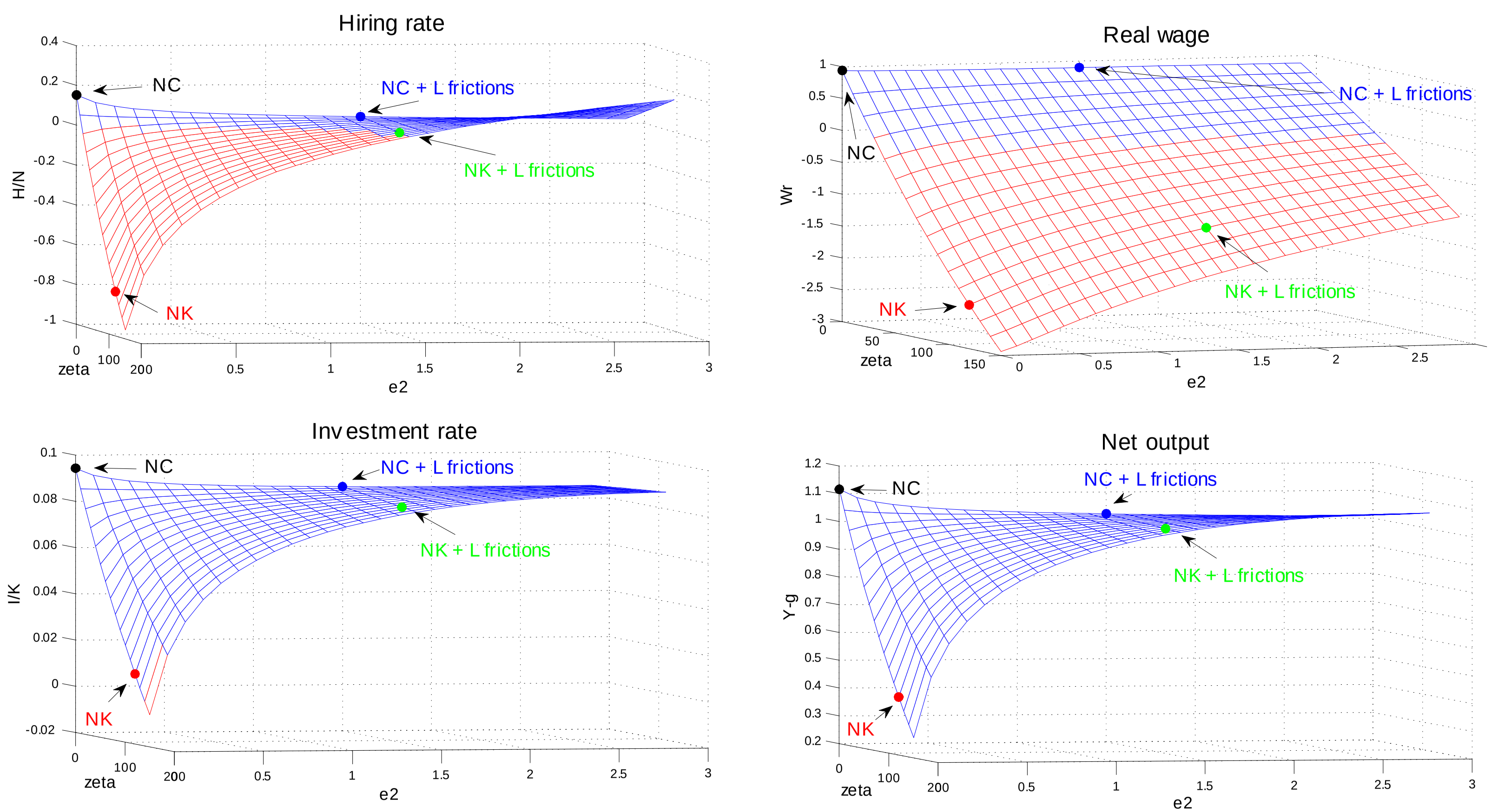
Notes: The figure shows impulse responses to a 25bp negative shock to the nominal interest rate, obtained in four benchmark parameterizations of the model: 1) the New Classical model (NC); 2) the New Classical model with labor and capital frictions (NC & LK frictions); 3) the New-Keynesian model (New Keynesian); 4) the New-Keynesian model with labor and capital frictions (New Keynesian and LK frictions).

Figure 3: Elasticity of marginal costs to a technology shock: hiring frictions model



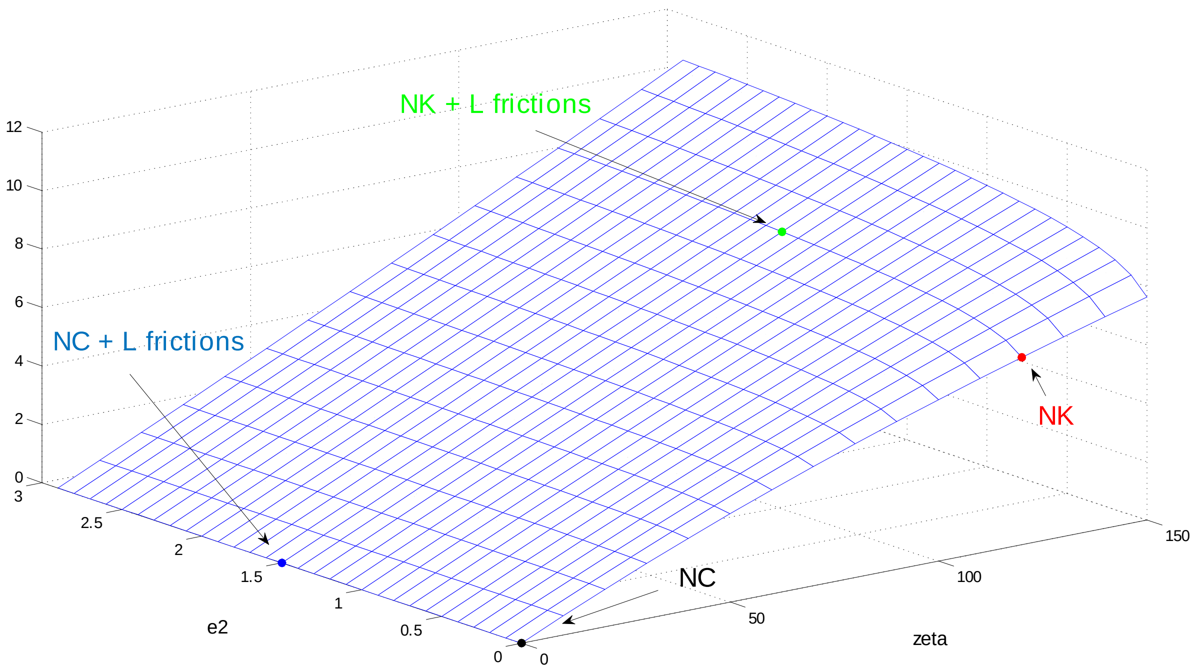
Notes: The figure shows the elasticity of marginal costs to technology shocks on the impact of the shock for different combinations of price rigidity, (ζ), and hiring frictions (e_2) in a model without investment frictions.

Figure 4: Impulse responses on impact of a technology shock: hiring frictions model



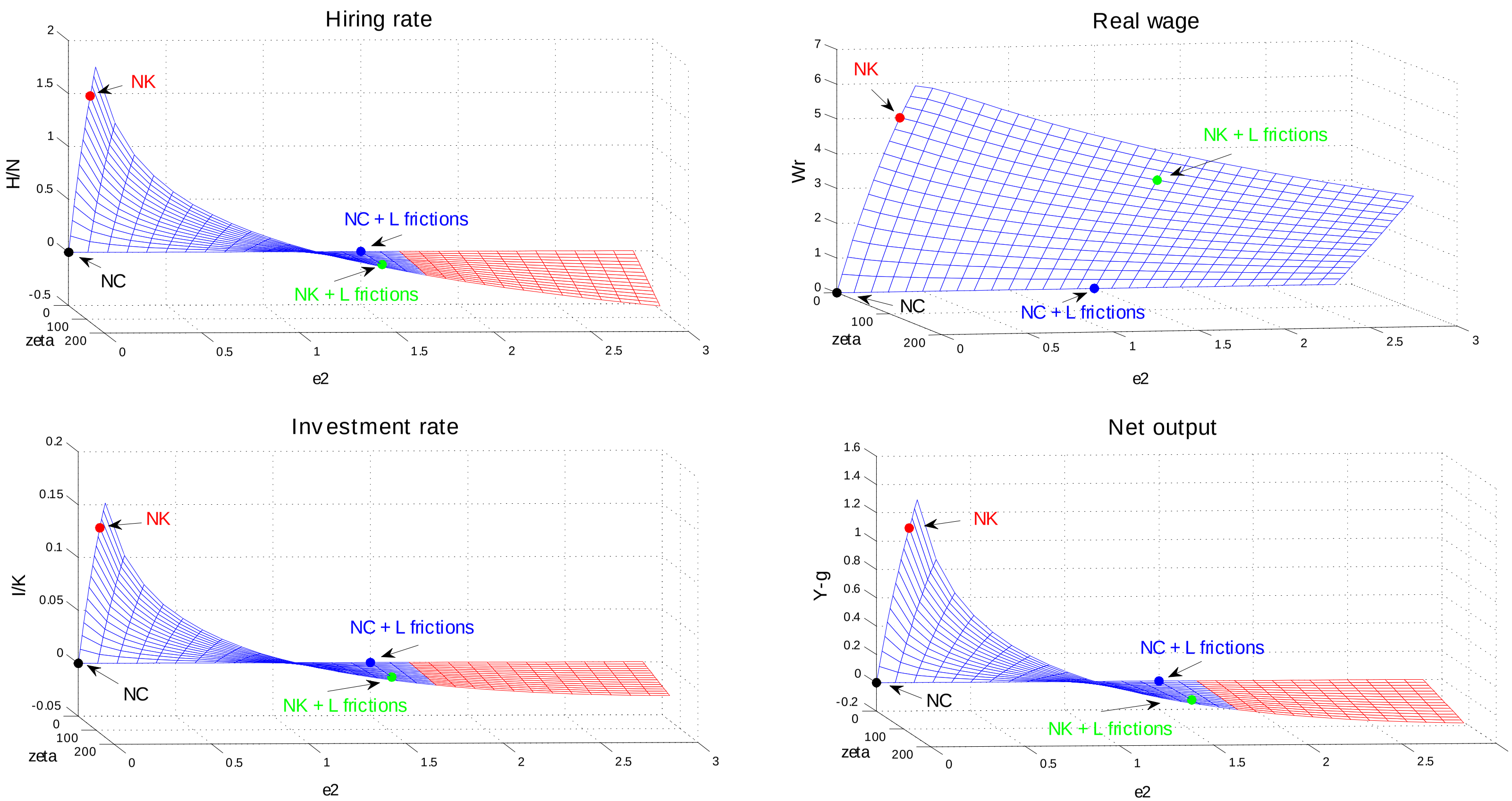
Notes: The figure shows impulse responses on the impact of a technology shock for various parameterizations of the model where we allow price rigidities, ζ, and hiring frictions, e_2, to vary, while shutting down investment frictions, i.e. setting $e_1 \simeq 0$.

Figure 5: Elasticity of marginal costs to a monetary shock: hiring frictions model



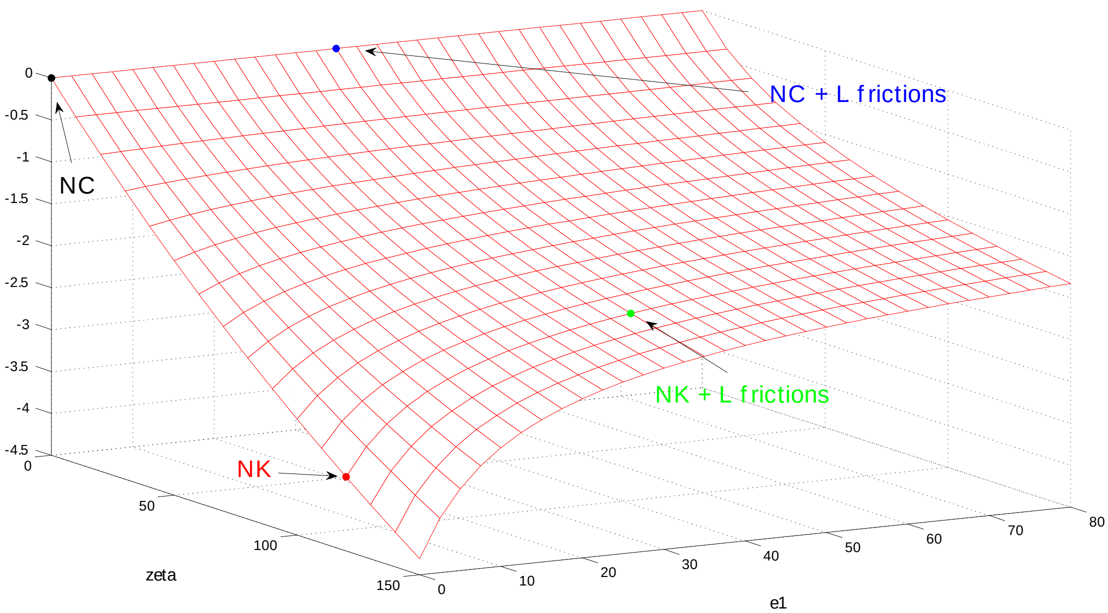
Notes: The figure shows the elasticity of marginal costs to monetary shocks on the impact of the shock for different combinations of price rigidity, (ζ), and hiring frictions (e_2) in a model without investment frictions.

Figure 6: Impulse responses on impact of a monetary shock: hiring frictions model



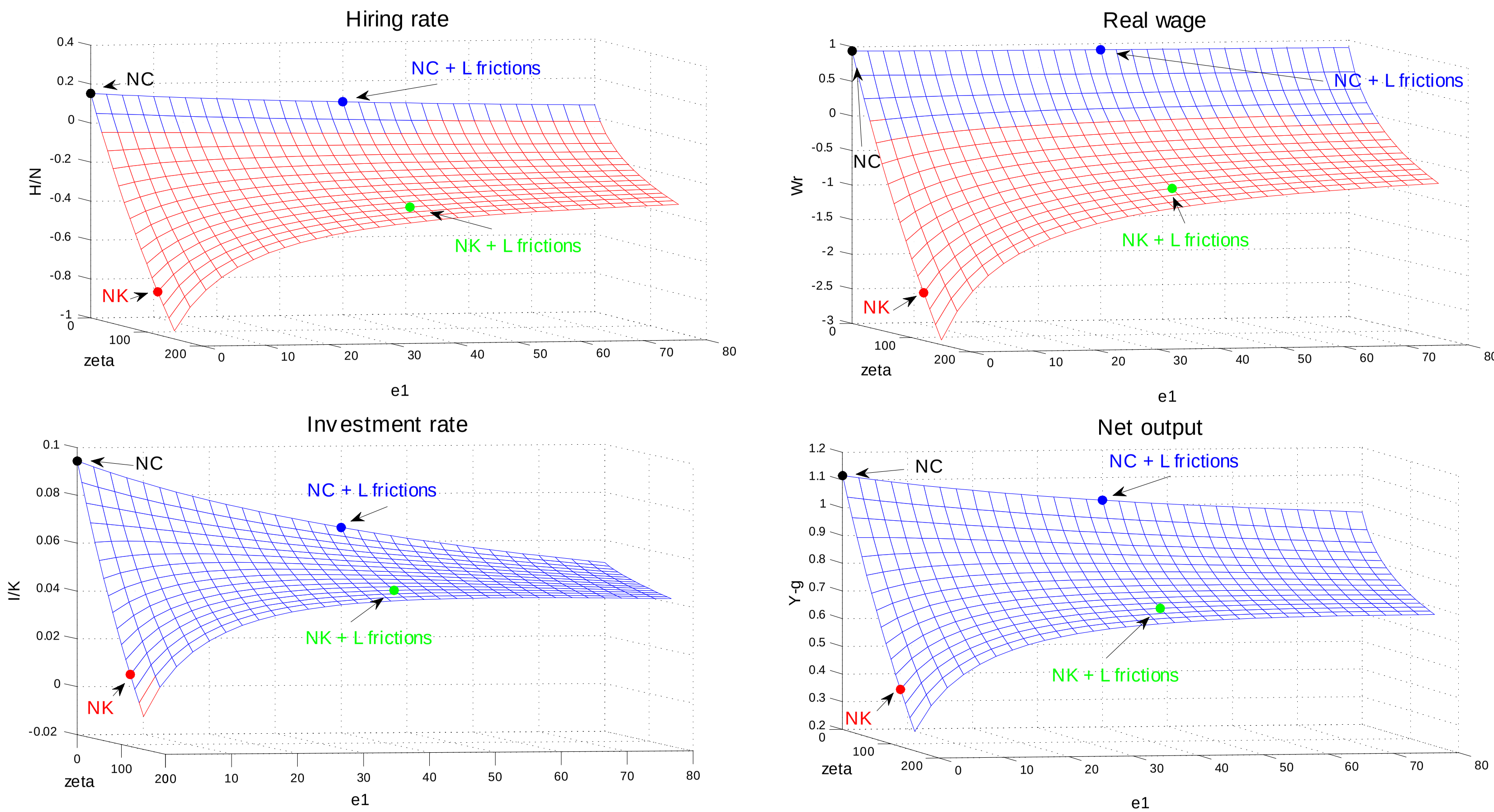
Notes: The figure shows impulse responses on the impact of a monetary shock for various parameterizations of the model where we allow price rigidities, ζ, and hiring frictions, e_2, to vary, while shutting down investment frictions, i.e. setting $e_1 \simeq 0$.

Figure 7: Elasticity of marginal costs to a technology shock: investment frictions model



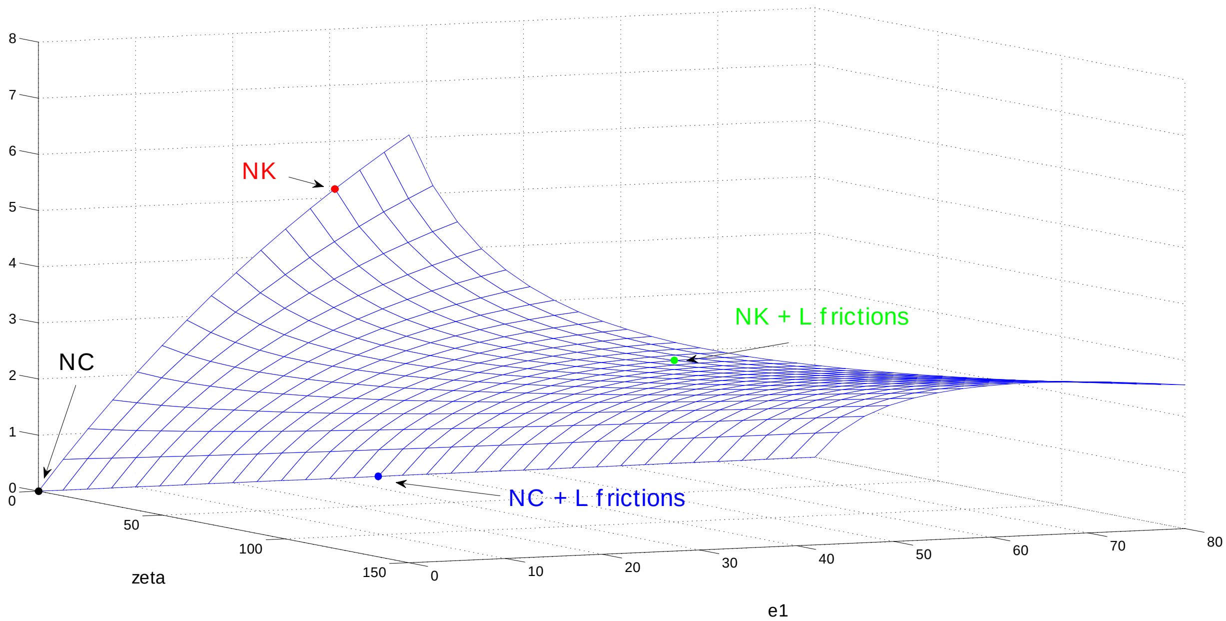
Notes: The figure shows the elasticity of marginal costs to technology shocks on the impact of the shock for different combinations of price rigidity (ζ) and investment frictions (e_1) in a model with no hiring frictions.

Figure 8: Impulse responses on impact of a technology shock: investment frictions model



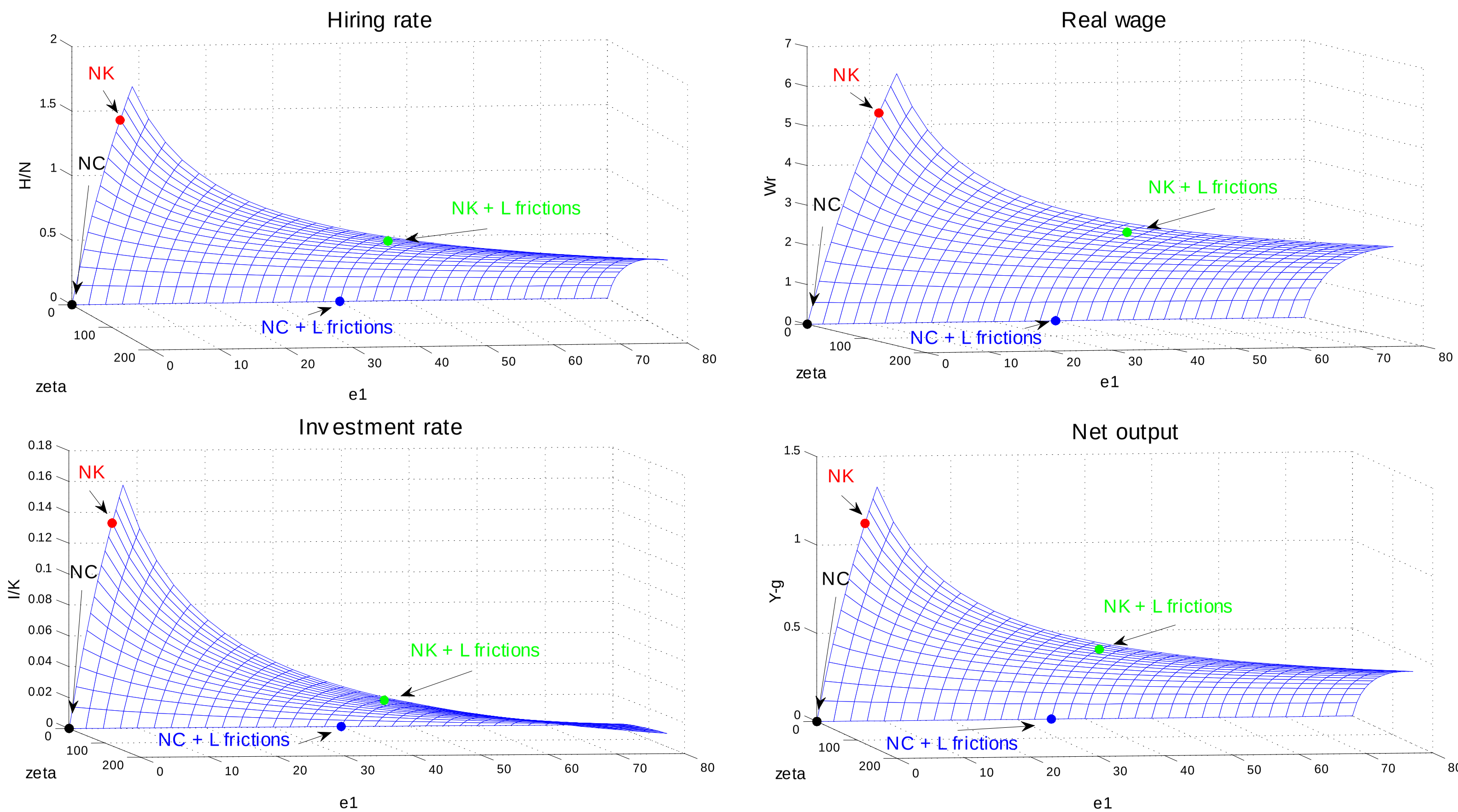
Notes: The figure shows impulse responses on the impact of a one percent technology shock for various parameterizations of the model where we allow price rigidities, ζ, and investment frictions, e_1, to vary, while shutting down hiring frictions, i.e. setting $e_2 \simeq 0$.

Figure 9: Elasticity of marginal costs to a monetary shock: investment frictions model



Notes: The figure shows the elasticity of marginal costs to monetary shocks on the impact of the shock for different combinations of price rigidity (ζ) and investment frictions (e_1) in a model without hiring frictions.

Figure 10: Impulse responses on impact of a monetary shock: investment frictions model



Notes: The figure shows impulse responses on the impact of a 25bp negative shock to the nominal interest rate for various parameterizations of the model where we allow price rigidities, ζ, and investment frictions, e_1, to vary, while shutting down hiring frictions, i.e. setting $e_2 \simeq 0$.