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ABSTRACT

We develop a simple quantitative New Keynesian model aimed at accounting for the recent sudden and persistent rise in inflation, with emphasis on the role of oil shocks and accommodative monetary policy. The model features oil as a complementary good for households and as a complementary input for firms. It also allows for unemployment and real wage rigidity. We estimate the key parameters by matching model impulse responses to those from identified money and oil shocks in a structural VAR. We then show that our model does a good job of explaining unemployment and inflation since 2010, including the recent inflation surge that began in mid 2021. We show that mainly accounting for this surge was a combination of oil price shocks and “easy” monetary policy, even after allowing for demand shocks and shocks to labor market tightness. Important for the quantitative impact of the oil price shock is a low elasticity of substitution between oil and labor, which we estimate to be the case.

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1 Introduction

From the mid 1990s to the summer of 2021, inflation remained relatively low and stable. This behavior re-enforced a conventional wisdom that so long as long term inflation expectations remained anchored, high inflation would remain a phenomenon of the past.¹ Seen in this context, the initial spurt in inflation in 2021 was thought by many (including the Federal Reserve!) to be transitory, the product of short-lived factors including a relative shift in spending from services to goods in conjunction with supply chain problems. However, high inflation has persisted through early 2023 with no immediate end in sight despite expectations remaining reasonably anchored and supply chain disruptions moderating.² These events suggest a clear need to revisit the sources of inflation.

We develop and estimate a simple New Keynesian model designed to account for the sources of the recent inflation surge. We place particular emphasis on two factors: first, the dramatic increase in oil prices which began in the summer of 2021 and accelerated in early 2022 in response to the Ukraine war; second, easy monetary policy in the form of the delayed response of the Federal Reserve to increasing inflation in 2021. Our framework also allows for other factors thought to be relevant including: increasing demand and shocks to labor market tightness. We show that even though we do not target inflation in our estimation, the model does a good job of explaining inflation since 2010, including the recent surge.

Section 2 presents the model, a variant of a standard New Keynesian framework with consumption goods only. In particular, we follow Blanchard and Gali (2007) in including oil as both a consumption good and an input into production. An important difference is that we allow for oil to be complementary with other consumption goods for households and a complementary input with labor for firms. As we make clear in section 4, the low elasticity of substitution between oil and labor (which we estimate) is essential to match quantitatively the impact of oil shocks on inflation.³ We also allow for

¹For evidence on the relative importance of long horizon inflation expectations for postwar inflation dynamics, see Hazell et al. (2022).

²Alcedo et al. (2022) shows that by April 2022, shortages for most categories of goods had moderated significantly since the peak two years earlier, with food being a notable exception.

³Bachmann et al. (2022) emphasize how oil being a strong complementary input enhances the impact of an oil shock on output. That is true in our case as well. We also

unemployment via search and matching in the labor market, which enables us to consider shocks to market tightness as a source of inflation. Finally, we add several features to the model which improve the empirical performance, including habit formation and real wage rigidity. For tractability we do not consider supply chain disruptions. As noted earlier, this factor appears to have moderated by the end of 2021 while our main interest is to explain the inflation that has persisted through 2022.

Section 3 describes how the model can produce inflation surges. We characterize how a low elasticity of substitution between oil and labor enhances the sensitivity of marginal cost and hence inflation to oil price shocks. We also describe how labor tightness affects marginal cost and inflation. We finally show, similar to Blanchard and Gali (2007), how real wage rigidity introduces a short run unemployment/inflation trade-off. This trade-off is important for understanding why the central bank may want to accommodate at least some of the inflation.

In section 4 we estimate the key parameters of the model. We do so by matching the model-implied impulse responses to a set of impulse responses from an estimated structural vector autoregression (SVAR). We consider two types of exogenous shocks. The first is a high frequency oil shock, identified as in Känzig (2021). The second is a high frequency shock to monetary policy, identified as in Gertler and Karadi (2015). Each shock serves as an external instrument in the SVAR. We choose to match impulse responses from both oil and money shocks to ensure the model responds well to both supply and demand disturbances.

In section 5 we present the results. We first show that the model impulse responses match well those from the SVAR for both the oil and money shocks. We then illustrate how complementarities enhance the impact of the oil price shock and also how the short run unemployment inflation trade-off matters.

In section 6 we explore how well the model accounts for recent inflation. We use the estimated model to perform a historical decomposition over the period 2010-22. We identify a set of core shocks by targeting a key set of real variables, leaving untargeted the nominal variables including headline and core inflation. We then show that mainly accounting for the inflation surge was a combination of oil price shocks and “easy” money shocks, even after controlling for shocks to demand and labor market tightness. Concluding remarks are in section 7.

emphasize the impact on inflation.

Related Literature. Before proceeding we briefly describe how our paper fits into the literature. As suggested earlier, our framework is most closely related to Blanchard and Gali (2007)’s New Keynesian model with oil and real wage rigidity. It differs by making oil a complementary good for households and a complementary input for firms. In addition we estimate the model as described earlier. Also relevant is a literature that estimates New Keynesian DSGE models with oil, including Soto and Medina (2005), Bodenstein and Guerrieri (2011), Bodenstein et al. (2012) and Blanchard and Riggi (2013) among others. We differ by estimating the model using observable shocks, including observable shocks to oil. In addition, our focus is on explaining the recent inflation surge. Our model also incorporates features thought to be relevant to recent events, such as labor market tightness, but at the same time is streamlined relative to the earlier DSGE literature.

Our paper is also connected to the rapidly growing literature on the recent inflation surge.⁴ As in Lorenzoni and Werning (2023) we emphasize the role of production complementarities and wage rigidity in inflation surges. A number of papers have emphasized the reallocation towards goods and supply chain problems to explain the rise in inflation in 2021, including Guerrieri et al. (2021), Comin and Johnson (2021), Ferrante et al. (2023), Di Giovanni et al. (2022). Our focus is more on the inflation that persisted through 2022 and the role of oil prices and monetary policy. Closer to our emphasis is Ball et al. (2022), Amiti et al. (2022), Benigno and Eggertsson (2023) and Pflueger (2023), though we differs significantly in approach and details.

2 The Model

The starting point is a standard New Keynesian model with consumption goods only. We add oil which is a complement good for households and a complement input for firms. There are two types of firms. Competitive wholesale firms produce intermediate goods using labor and oil. These firms add workers via a search and matching process. The wholesale firms then sell their output to monopolistically competitive retailers that package the intermediate input into final goods. Retailers also set nominal prices on a staggered basis, which introduces nominal price rigidity as in the standard NK model. We also introduce several features that improve the empirical performance of the model, including habit formation and real wage rigidity.

⁴See Reis (2022) for an overview of possible explanations for the recent inflation.

We next describe the elements of the model.

2.1 Households

There is a representative household with a continuum of members of measure unity. The number n_t of members are currently employed. The household provides perfect consumption insurance for its members. Family members currently not employed look for a job. A search and matching process that we describe shortly determines employment n .

Each period the household consumes a composite c_t that is the following CES aggregate of final consumption goods c_{qt} and oil c_{ot} :

$$c_t = \left(\chi^{\frac{1}{\psi}} c_{ot}^{1-\frac{1}{\psi}} + (1-\chi)^{\frac{1}{\psi}} c_{qt}^{1-\frac{1}{\psi}} \right)^{\frac{1}{1-\frac{1}{\psi}}} \quad (1)$$

where $\psi > 0$ is the elasticity of substitution between the two goods: As we show later, our estimates suggest that $\psi < 1$, implying the goods are complements. Finally, c_{qt} is a composite of a continuum of differentiated retail consumption goods, but we defer a description of the demand for these differentiated goods until later.

Let β be the subjective discount factor and ε_{bt} a discount factor shock (effectively a demand shock.) Then the household's objective depends on the utility gain from consumption, as follows:

$$E_t \sum_{i=0}^{\infty} \beta^i \varepsilon_{bt} \ln(c_{t+i} - hc_{t-1+i}) \quad (2)$$

where $h \in [0, 1]$ is the degree of habit persistence. As is standard, we allow for habit formation to capture the hump-shaped dynamics in real activity that is present in the data (as we elaborate shortly).

The household receives wage income from its employed members and unemployment insurance from the unemployed ones. Let w_{ct} denote the real wage and b_t unemployment insurance, both in units of the consumption composite. In addition, the household has the option of saving in the form of a nominal bond B_t that pays the gross nominal rate rate R_t^n . Let p_{ct} be the nominal price of c_t : The overall budget constraint is then given by:

$$c_t = w_{ct}n_t + b_t(1 - n_t) + R_{t-1}^n \frac{p_{ct-1}}{p_{ct}} B_{t-1} - B_t + \Pi_t \quad (3)$$

where Π_t is total net payments to the household, which includes dividends from ownership of firms and net lump sum taxes paid to the government. Conditional on n_t , the household chooses c_t, B_t, c_{qt} and c_{ot} to maximize (2) given (3) and (1).

Let u_{ct} be the marginal utility of consumption:

$$u_{ct} = \frac{1}{c_t - hc_{t-1}} - \frac{\beta h}{c_{t+1} - hc_t} \quad (4)$$

Then from the household's consumption/saving decision:

$$1 = E_t \left\{ \Lambda_{t,t+1} R_t^n \frac{p_{ct}}{p_{ct+1}} \right\} \quad (5)$$

where $R_t^n \frac{p_{ct}}{p_{ct+1}}$ is the real return on the nominal bond and $\Lambda_{t,t+1} = \beta \frac{u_{ct+1}}{u_{ct}}$ is the household's stochastic discount factor.

Next, let p_{qt} and p_{ot} be the nominal prices of c_{qt} and c_{ot} , respectively, and $s_t = p_{ot}/p_{ct}$ the relative price of oil. From cost minimization we obtain demand functions for consumption goods and oil:

$$c_{qt} = (1 - \chi) \left(\frac{p_{qt}}{p_{ct}} \right)^{-\psi} c_t \quad (6)$$

$$c_{ot} = \chi s_t^{-\psi} c_t \quad (7)$$

Combining (6) and (7) with (1) yields a price index for p_{ct} :

$$p_{ct} = \left(\chi p_{ot}^{1-\psi} + (1 - \chi) p_{qt}^{1-\psi} \right)^{\frac{1}{1-\psi}} \quad (8)$$

2.2 Unemployment, Vacancies and Matching

As we noted earlier, production and employment take place in the wholesale sector. We describe wholesale firms shortly. In the meantime we characterize the search and matching process. The approach follows closely Mortensen and Pissarides (1994). At time t , each wholesale firm i employs $n_t(i)$ workers and posts $v_t(i)$ vacancies to attract new workers. To post each vacancy a firm must pay the fixed cost c . Total employment and vacancies are given by $n_t = \int_0^1 n_t(i) di$ and $v_t = \int_0^1 v_t(i) di$. All unemployed workers at t look for jobs. We assume that those unemployed who find a job go to work immediately

within the period (in contrast to the standard formulation where they wait a period). Accordingly, the stock u_t of unemployed workers entering period t is the difference between the labor force (which we fix at unity) and the stock n_{t-1} of employed workers at the end of $t - 1$:

$$u_t = 1 - n_{t-1} \quad (9)$$

The number of new hires Φ_t is governed by the following matching function with constant returns to scale that is increasing in both vacancies and unemployment:

$$\Phi_t = \varepsilon_{\Phi t} u_t^\sigma v_t^{1-\sigma} \quad (10)$$

where the random variable $\varepsilon_{\Phi t}$ is a shock to match efficiency. Alternatively, the shock could also reflect shifts in search effort by the unemployed or recruiting intensity by firms. Note that a decline in $\varepsilon_{\Phi t}$ acts like a negative shock to labor supply. It also can increase labor market tightness as the drop in $\varepsilon_{\Phi t}$ implies that a rise in vacancies is need to create the same amount of matches.

Next, the probability q_t a firm fills a vacancy in period t is given by:

$$q_t = \frac{\Phi_t}{v_t} \quad (11)$$

In turn, the probability a worker finds a job f_t is:

$$f_t = \frac{\Phi_t}{u_t} \quad (12)$$

Firms and workers take both q_t and f_t as given.

Finally, each period an exogenous fraction of workers $1 - \rho$ separate from the firm at which they were employed and become unemployed.

2.3 Wholesale Firms

Competitive wholesale firms produce and sell output to retail firms. Wholesale firm i makes output y_t using input of labor n_t and oil o_t according to the following CES production (where we drop the firm subscript i for convenience):

$$y_t = \left(\alpha^{\frac{1}{\epsilon}} n_t^{1-\frac{1}{\epsilon}} + (1 - \alpha)^{\frac{1}{\epsilon}} o_t^{1-\frac{1}{\epsilon}} \right)^{\frac{1}{1-\frac{1}{\epsilon}}} \quad (13)$$

where ϵ is the elasticity of substitution between labor and oil. As we show, our estimates suggest a value of ϵ well below unity, implying that oil and labor are strong complementary inputs.⁵

Employment at t is the sum of surviving workers from the previous period, ρn_{t-1} and new hires, where the latter is the product of the vacancy filling probability and total vacancies, $q_t v_t$. That is, we can write:

$$n_t = \rho n_{t-1} + q_t v_t \quad (14)$$

The firm can thus adjust current employment by posting vacancies, taking q_t as given.⁶

We next turn to the firm's objective. Let p_{wt} be the wholesale firm's relative price, $w_{qt} = w_{ct}(p_{ct}/p_{qt})$ the real product wage and (as before), $s_{qt} = s_t(p_{ct}/p_{qt})$ the relative price of oil, all in units of final good output. The firm's objective then is to maximize the discounted stream of profits, F_t , given by:

$$F_t = p_{wt}y_t - w_{qt}n_t - cv_t - s_{qt}o_t + E_t \{ \Lambda_{t,t+1}^q F_{t+1} \} \quad (15)$$

where $\Lambda_{t,t+1}^q = \beta \left(\frac{u_{ct+1}}{u_{ct}} \right) \left(\frac{p_{qt+1}/p_{ct+1}}{p_{ct}/p_{qt}} \right)$ is the household's stochastic discount factor in terms of final good output. Note that profits each period are the difference between revenues $p_{wt}y_t$ and the sum of the wage bill $w_{qt}n_t$, vacancy posting costs cv_t and oil costs $s_{qt}o_t$. The optimization problem is then the following: firms choose vacancies v_t , employment n_t and oil o_t to maximize (15) subject to (13) and (14).

Let a_{nt} be the marginal product of labor. The first order conditions for v_t and n_t along with the envelope condition yield the following standard first order condition for hiring:

$$\begin{aligned} \frac{c}{q_t} &= \sum_{i=0}^{\infty} \rho^i E_t \{ \Lambda_{t,t+i}^q (p_{wt+i} a_{nt+i} - w_{qt+i}) \} \\ &= p_{wt} a_{nt} - w_{qt} + \rho E_t \left\{ \Lambda_{t,t+1}^q \frac{c}{q_{t+1}} \right\} \end{aligned} \quad (16)$$

where the marginal product of labor is:

$$a_{nt} = \left(\alpha \frac{y_t}{n_t} \right)^{\frac{1}{\epsilon}} \quad (17)$$

⁵See for example Bachmann et al. (2022).

⁶We assume the law of large numbers applies so that $q_t v_t$ is with certainty the number of new hires.

The left-hand side of equation (16) is the marginal cost of adding a worker, given by the vacancy-posting cost divided by the probability of filling the vacancy, while the right-hand side is the marginal benefit of an extra worker, given by the expected discounted stream of the per-period profits $p_{wt+i}a_{nt+i} - w_{qt+i}$.

Let a_{ot} be the marginal product of oil. The firm's demand for oil is given by the condition that the marginal value of oil equals the marginal cost:

$$p_{wt}a_{ot} = s_{qt} \quad (18)$$

where the marginal product of oil is:

$$a_{ot} = \left((1 - \alpha) \frac{y_t}{o_t} \right)^{\frac{1}{\epsilon}} \quad (19)$$

So far we have described the firm's hiring decision conditional on the path of wages. We will describe shortly how wages are determined. In the meantime it is useful to characterize the value J_t of a worker to the firm, after hiring costs have been paid. From differentiating equation (15) with respect to n_t and applying the envelope theorem we obtain:

$$\begin{aligned} J_t &= \sum_{i=0}^{\infty} E_t \{ \Lambda_{t,t+i}^q (p_{wt}a_{t+i} - w_{qt+i}) \} \\ &= p_{wt}a_t - w_{qt} + \rho E_t \{ \Lambda_{t,t+1}^q J_{t+1} \} \end{aligned} \quad (20)$$

2.4 Workers

We next develop an expression for the worker's surplus from a job, which is critical for wage determination. Recall that $w_{ct} = w_{qt}(p_{qt}/p_{ct})$ is the real wage in units of the consumption composite. Let V_t be the value to a worker of employment at t and U_t the value of being unemployed. Then V_t and U_t are given by:

$$V_t = w_{ct} + E_t \{ \Lambda_{t,t+1} (\rho V_{t+1} + (1 - \rho)U_{t+1}) \} \quad (21)$$

$$U_t = b_t + E_t \{ \Lambda_{t,t+1} (f_{t+1}V_{t+1} + (1 - f_{t+1})U_{t+1}) \} \quad (22)$$

where w_{ct} and $b_t = b(p_{qt}/p_{ct})$ are the flow values of work and unemployment respectively, ρ is the job survival probability and f_{t+1} is the probability of moving from unemployment in t to employment in $t + 1$.

The job surplus H_t is then given by:

$$\begin{aligned} H_t &= V_t - U_t \\ &= w_{ct} - b_t + E_t \{ \Lambda_{t,t+1} ((\rho - f_{t+1})H_{t+1}) \} \end{aligned} \quad (23)$$

2.5 Wage Determination

We introduce now a simple form of real wage rigidity. We assume that the wage depends on the gap between the value that would arise under Nash bargaining and its steady state value. The degree of stickiness is parsimoniously characterized by a single parameter that we estimate. We elaborate below.

2.5.1 Nash Bargaining Wage

Let us start by characterizing the product wage under Nash bargaining. In this hypothetical case the firm and its workers choose w_{qt} to maximize the joint surplus from the match, as follows⁷:

$$\max_{w_{qt}} H_t^\varsigma J_t^{1-\varsigma} \quad (24)$$

where $\varsigma \in [0, 1]$ is the relative bargaining power of workers and H_t and J_t are as in equations (20) and (23). Maximizing with respect to w_{qt} yields the following conventional first order condition that relates the relative surpluses to the bargaining weights:

$$\frac{J_t}{H_t} = \frac{1 - \varsigma}{\varsigma} \quad (25)$$

Combining (20), (23) and (25) leads to the product wage that would arise under Nash Bargaining:

$$w_{qt}^o = \frac{\varsigma \left(p_{wt} a_{nt} + \rho E_t \left\{ \frac{c}{q_{t+1}} (\Lambda_{t,t+1}^q - \Lambda_{t,t+1}) \right\} + E_t \{ \Lambda_{t,t+1} c \theta_{t+1} \} \right) + (1 - \varsigma) \frac{p_{qt} b}{p_{ct}}}{\varsigma + (1 - \varsigma) \frac{p_{qt}}{p_{ct}}} \quad (26)$$

As is standard, the Nash wage is a convex combination of the period surplus the worker brings to the match and the worker's outside option, where the weights depend on relative bargaining power. The term $\rho E_t \left\{ \frac{c}{q_{t+1}} (\Lambda_{t,t+1}^q - \Lambda_{t,t+1}) \right\}$

⁷Notice that the outcome is the same with bargaining over the consumption wage w_{ct} .

reflects differences in the evaluation of the value of a worker due to differences in the stochastic discount factors. The presence of the relative price of goods, p_{qt}/p_{ct} , reflects how workers value the nominal wage and unemployment insurance payments differently from firms.

In what follows, we assume that the bargaining weight ζ and $1 - \zeta$ equal the corresponding weights σ and $1 - \sigma$ in the matching function, implying the Hosios condition holds: The equilibrium with wages determined by Nash bargaining is thus constrained efficient, in the sense that the social value of the marginal hire equals the marginal recruiting cost.

2.5.2 Real Wage Rigidity

As Shimer (2005) observes, period-by-period Nash bargaining over wages leads to unemployment volatility that is too low relative to the data and wage volatility that is too high. Further, as suggested by Blanchard and Gali (2007), absent any frictions in wage determination it is difficult to explain large effects of oil price shocks, as wages could freely adjust to dampen the impact on the economy.

Therefore, we follow Blanchard and Gali (2007) in introducing real wage rigidity. We suppose that the percent adjustment of the real wage relative to steady state is the fraction $1 - \gamma$ of the percent fluctuation in the Nash wage w_{qt}^o , where $\gamma \in [0, 1]$. In particular,

$$w_{qt} = (w_{qt}^o)^{1-\gamma}(w_q)^\gamma \quad (27)$$

where w_q is the steady state Nash wage. Under reasonable parametrizations, equation (27) is consistent with rational behavior as it lies within the bargaining set, i.e. it is never above firm's reservation wage (the value to the firm of a worker) nor it is ever below worker's reservation wage (the flow value of unemployment). One way to interpret equation (27) is as the firm providing some insurance to workers by offering a smoother real wage than would be the case under period-by-period Nash bargaining. Though we do not motivate this argument from first principles.⁸

Finally, note that the parameter γ reflects the degree of real wage rigidity. We will estimate this parameter.

⁸See Gertler and Trigari (2009) and Christiano et al. (2016) for formal models of real wage rigidity in a search and matching setting.

2.6 Retail Firms

There is a continuum of monopolistically competitive retail firms indexed by $j \in [0, 1]$. Retailers buy intermediate goods from the wholesale firms described earlier. Retailers then transform intermediate goods into a differentiated final good. Households buy and consume these differentiated products. Finally, retail firms set prices on a staggered basis. They obey a standard time-dependent rule following Calvo: We suppose $1 - \lambda$ is the probability the firm is able to change price in the current period, where the draw is i.i.d across time and firms.

The consumption good composite for each household c_{qt} , is given by the CES aggregate of each retail firm's output y_{jt} , as follows:

$$c_{qt} = \left(\int_0^1 y_{jt}^{\frac{\eta}{\eta-1}} dj \right)^{\frac{\eta-1}{\eta}} \quad (28)$$

where η is the elasticity of substitution across intermediate goods. From cost minimization we obtain the household's demand for each retail good as an inverse function of the relative price p_{jt}/p_{qt} along with an expression for the price of final consumption goods p_{qt} :

$$y_{jt} = \left(\frac{p_{jt}}{p_{qt}} \right)^{-\eta} c_{qt} \quad (29)$$

$$p_{qt} = \left(\int_0^1 p_{jt}^{1-\eta} dj \right)^{\frac{1}{1-\eta}} \quad (30)$$

In each period, the fraction λ of retail firms that are unable to adjust price simply meet demand for their differentiated final good. They do so by buying enough input from wholesalers as long as the relative output price $\frac{p_{jt}}{p_{qt}}$ is not less than the cost of inputs p_{wt} .

On the other hand, retail firms that are able to adjust price within the period choose the reset price p_{jt}^* and output y_{jt} to maximize expected discounted profits, subject to the demand curve (29):

$$\max_{p_{jt}^*, y_{jt}} E_t \left\{ \sum_{i=0} \lambda^i \Lambda_{t,t+i}^q \left(\frac{p_{jt}^*}{p_{qt}} - p_{wt} \right) y_{jt+i} \right\} \quad (31)$$

where the probability λ^i that the firm's price remains fixed i periods into the future. Note that the relative wholesale price p_{wt} corresponds to the marginal cost of production.

The standard first order condition for the retailer's reset price is given by:

$$E_t \left\{ \sum_{i=0}^{\infty} \lambda^i \Lambda_{t,t+i}^q \left(\frac{p_{jt}^*}{p_{qt+i}} - (1 + \mu)p_{wt+i} \right) y_{jt+i} \right\} = 0 \quad (32)$$

where $\mu = 1/(1 - 1/\eta)$ is desired net markup. When able to adjust, a firm chooses to reset the price p_{jt}^* so that, over the period in which its price is expected to remain fixed, its relative price equals a discounted weighted average of the desired gross gross markup $(1 + \mu)$ over its real marginal cost p_{wt+i} .

Finally, using the law of large numbers, we can rewrite the price index as:

$$p_{qt} = \left((1 - \lambda)(p_t^*)^{1-\eta} + \lambda p_{t-1}^{1-\eta} \right)^{\frac{1}{1-\eta}} \quad (33)$$

Equations (32) and (33) govern the path of goods inflation conditional on real marginal cost p_{wt} .

2.7 The Oil Market and Resource Constraints

We suppose that there is a representative oil producer who acts competitively. Each period the producer receives an endowment of oil equal to $S \exp(-\varepsilon_{ot})$, where ε_{ot} is a shock to the oil supply and S is the steady-state oil supply. The producer takes the price of oil as given. All profits are paid out as dividends to households. Each period the sum of the firm demand for oil o_t and the household demand c_{ot} must equal the total supply, as follows:

$$o_t + c_{ot} = S \exp(-\varepsilon_{ot}) \quad (34)$$

where the respective firm and household oil demand functions are given by equations (7) and (18). The relative price of oil s_t adjusts to clear the market.

In practice, of course, the supply of available energy depends not only on currently produced oil but inventory behavior, which in turn can involves speculative dynamics. Given we are estimating our model, we abstract from inventories. In the end, though, our estimated model will capture observed oil price dynamics which is what is critical for macroeconomic behavior.

For produced goods, the relevant resource constraint is given by the condition that consumption goods c_{qt} must equal output y_{qt} net hiring costs cv_t :

$$c_{qt} = y_{qt} - cv_t \quad (35)$$

Finally, the supply of nominal bonds is zero:

$$B_t = 0 \tag{36}$$

2.8 Government Policy

We suppose that central bank adjusts its instrument, the nominal interest rate, according to a simple Taylor rule augmented by a persistent exogenous money shock ε_{rt} :

$$R_t^n = R^n \pi_{qt}^{\phi_\pi} e^{\varepsilon_{rt}}$$

where ϕ_π is the feedback coefficient on inflation.

The only fiscal expenditures are unemployment insurance payments. We suppose payments are financed by lump sum taxes on households

$$b_t u_t = \tau_t$$

This completes the description of the model.

3 Sources of Inflation Surges

We now characterize the features of our model that can help account for inflation surges. As discussed in section 2.6, inflation depends on the real marginal cost of final goods firms. In our model, this cost corresponds to the relative price of wholesale goods p_{wt} . Let $\pi_{qt} = \ln(p_{qt}/p_{qt-1})$ be goods market inflation and $\widehat{p}_{wt} = \ln(p_{wt}/p_w)$ be the log deviation of the relative wholesale price from its steady state. Loglinearizing (32) around the zero inflation steady state and using equation (33), then yields the following Phillips curve relation for π_{qt} :

$$\pi_{qt} = \kappa \widehat{p}_{wt} + E_t\{\pi_{qt+1}\} \tag{37}$$

where $\kappa = (1 - \lambda)(1 - \lambda\beta)/\lambda$. As in the standard NK formulation, inflation depends on real marginal cost, which in this case is \widehat{p}_{wt} .

We next decompose the movement in p_{wt} into three terms: the real wage, the marginal hiring cost and the marginal product of labor. As we show, all three factors could play a significant role in an inflation surge. However, given strong complementarities between labor and oil, the marginal product of labor plays a particularly important role.

From the hiring condition (16) we can derive a relation for the marginal hiring cost. Let ω_t be the net marginal cost of hiring a worker.⁹ From equation (16), we can express ω_t as:

$$\omega_t = \frac{c}{q_t} - \rho E_t \left\{ \Lambda_{t,t+1}^q \frac{c}{q_{t+1}} \right\} \quad (38)$$

which is the gross cost of adding a worker at t , c/q_t , net the expected discounted benefit that the additional worker at t will generate in the future $\rho E_t \left\{ \Lambda_{t,t+1}^q c/q_{t+1} \right\}$.¹⁰ We can then express the marginal cost of producing a unit of output as the sum of the wage w_{qt} and net hiring costs ω_t , normalized by the marginal product of labor a_{nt} , as follows:

$$p_{wt} = \frac{w_{qt} + \omega_t}{a_{nt}} \quad (39)$$

Recall that the marginal product of labor is $a_{nt} = (\alpha y_t/n_t)^{\frac{1}{\epsilon}}$.

From loglinearizing equation (39), we can decompose marginal cost \hat{p}_{wt} into a convex combination of the real product wage \hat{w}_{qt} and net hiring costs $\hat{\omega}_t$ minus the marginal product of labor \hat{a}_{nt} , all expressed in log deviations from steady state:

$$\hat{p}_{wt} = \zeta \hat{w}_{qt} + (1 - \zeta) \hat{\omega}_t - \hat{a}_{nt} \quad (40)$$

where $\zeta = \frac{w_q}{w_q + \omega}$. There are two significant differences from the formulation of marginal cost in standard New Keynesian models:

First, the presence of complementarities enhances the sensitivity of the marginal product of labor (and hence marginal cost) to fluctuations in oil intensity, measured by the ratio of oil to labor input, o_t/n_t . After combining equations (13) and (17), we can obtain the following loglinear approximation for the marginal product of labor

$$\hat{a}_{nt} = \frac{1}{\epsilon} (1 - \bar{\alpha}) (\hat{o}_t - \hat{n}_t) \quad (41)$$

with:

$$\bar{\alpha} = \frac{\alpha}{\alpha + \alpha^{1-\frac{1}{\epsilon}} (1 - \alpha)^{\frac{1}{\epsilon}} \left(\frac{\rho}{n}\right)^{1-\frac{1}{\epsilon}}} \approx \alpha$$

⁹Ferrante et al. (2023) also develop a role for hiring costs in affecting marginal cost in their model of sectoral reallocation with quadratic labor adjustment costs.

¹⁰From the hiring condition, we can infer that c/q_{t+1} equals the present value of earnings at $t+1$ and beyond generated by a worker who is with the firm at t . From the vantage of time t we take expectations and discount this value by the job survival probability ρ and the household stochastic discount factor $\Lambda_{t,t+1}^q$.

Note first that under our calibration $\bar{\alpha} \approx \alpha$ since $o/n \approx (1 - \alpha)/\alpha$. The equation then makes clear how as the complementarity increases (i.e., the elasticity of substitution ϵ declines) the sensitivity of \hat{a}_{nt} to $\hat{o}_t - \hat{n}_t$ increases. As we will see, with sufficient complementarity, a large oil shock which reduces oil intensity can produce a sharp decline in \hat{a}_{nt} contributing to a surge in inflation via its impact on marginal cost.¹¹ An accompanying demand shock will enhance the inflation surge by increasing employment, pushing down further \hat{a}_{nt} . In what follows we will argue that such a combination of supply and demand shocks is what produced the inflation surge in 2021/22.

Second, labor market tightness $\theta_t = (v_t/u_t)$ affects marginal cost. Note first that from equations (10) and (11) the vacancy filling probability q_t varies inversely with tightness, as follows:

$$q_t = \varepsilon_{\Phi t} \theta_t^{-\sigma} \quad (42)$$

Using equations (38) and (42), we can express net hiring costs as a linear function of current and expected market tightness:

$$\hat{\omega}_t = \frac{1}{1 - \rho\beta} E_t \left\{ \sigma \hat{\theta}_t - \rho\beta \sigma \hat{\theta}_{t+1} - \rho\beta \hat{\Lambda}_{t,t+1}^q + \ln \varepsilon_{\Phi t} - \rho\beta \ln \varepsilon_{\Phi t+1} \right\} \quad (43)$$

Equations (40) and (43) illustrate how, via net hiring costs $\hat{\omega}_t$, market tightness $\hat{\theta}_t$ affects marginal cost \hat{p}_{wt} . In addition, from equation (26), the real wage is increasing in expected labor market tightness as the latter increases the value of unemployment. Both forces imply that a tightening of labor market conditions raises marginal cost, which thus applies upward pressure on prices.

Finally, the conduct of monetary policy is critical. How much inflation emerges from forces that put upward pressure on marginal cost ultimately depends on the degree of monetary accommodation. For example, if the central bank tightens sufficiently, inflation will not increase. The question then becomes whether there is a short run trade-off between inflation and (the efficient level of) real activity that might induce some accommodation from the central bank. Absent such a trade-off there is no reason for a central bank to accommodate the inflationary pressures.

As in Blanchard and Gali (2007), a short run trade-off between inflation and real activity arises due to the presence of real wage rigidity. Since we

¹¹Wage rigidity also matters. Absent adjustment frictions, wages may drop significantly, moderating the impact of the oil shock on marginal cost.

differ in a number of details, it is useful to illustrate how this trade-off arises within our framework. First suppose that retail firms receive lump sum subsidies so that there is no distortion from imperfect competition in the flexible price equilibrium. Then with sticky prices and flexible wages, monetary policy can achieve the first best outcome by setting demand so that the markup $1/p_{wt}$ equals its first best value $1 + \mu$. In this instance, inflation will equal its optimal value of zero (since \widehat{p}_{wt} in the Phillips curve (37) will be zero). Hiring and employment will also be efficient, given the wage is set each period by Nash bargaining and our parametric assumptions ensure that the Hosios conditions is satisfied. Hence, absent real wage rigidity there is no trade-off.

Now consider real wage rigidity. Let \widehat{p}_{wt}^o be the “Nash” marginal cost, i.e. the marginal cost if wages were determined each period by Nash bargaining. It follows from equation (27) that we can express marginal cost in this instance as

$$\begin{aligned}\widehat{p}_{wt} &= \zeta(1 - \gamma)\widehat{w}_{qt}^o + (1 - \zeta)\widehat{w}_t - \widehat{a}_{nt} \\ &= \widehat{p}_{wt}^o - \gamma\widehat{w}_{qt}^o\end{aligned}\tag{44}$$

Equation (44) makes clear that in this case the wage only adjusts partially to the Nash wage, by the factor $1 - \gamma$. Notice that with wage rigidity ($\gamma > 0$), actual marginal cost \widehat{p}_{wt} differs from its value under Nash bargaining \widehat{p}_{wt}^o .

We can illustrate the trade-off by combining (44) with the loglinearized Phillips curve to obtain

$$\pi_{qt} = \kappa\widehat{p}_{wt}^o + E_t\pi_{qt+1} + \Delta_t\tag{45}$$

where the cost push term depends on the deviation of the wage from the Nash wage as follows

$$\Delta_t = -\kappa\gamma\widehat{w}_{qt}^o$$

Absent real wage rigidity ($\gamma = 0$), Δ_t goes to zero, implying no trade-off.

However, with $\gamma > 0$ and supply shocks to the economy, it is not possible to simultaneously achieve price stability along with the efficient level of economic activity. Consider a negative oil supply shock. The shock puts upward pressure on marginal cost by reducing the marginal product of labor a_{nt} . It also reduces the Nash wage. But due to the rigidity, the actual wage falls by less than the Nash wage, implying an increase in the cost push term Δ_t . If the central bank chooses to adjust demand to keep \widehat{p}_{wt}^o to zero, then the cost push term will generate an increase in inflation. If it chooses to not accommodate the inflation, it must contract demand to push \widehat{p}_{wt}^o negative in order

to offset the impact of the cost push term.¹² The net effect is that stabilizing prices in response to the oil shock requires reducing economic activity below the efficient level, something that would not be necessary if wages were fully flexible. Accordingly, the supply shock confronts the central bank with a short run trade-off, which provides a rationale for why it may accommodate some of the inflationary pressures. We illustrate this trade-off later with our estimated model.¹³

4 Model Estimation

We estimate the key parameters of the model by matching the model-implied impulse responses to a set of impulse responses generated from an estimated structural vector autoregression (SVAR). The SVAR contains a set of macroeconomic variables that have representations in the model. We consider two types of observable shocks that serve as external instruments in our estimated SVAR: a supply shock and a demand shock. The supply shock is a high frequency oil shock, identified as in Känzig 2021. The demand shock is a high frequency shock to monetary policy, obtained as in Gertler and Karadi 2015.

Section 4.1 describes the data. In section 4.2 we discuss the identification of the shocks. In section 4.4 we introduce the methodology used for matching the impulse responses and estimating confidence intervals for the parameters. Finally, in section 5 we present the model fit and the results from the estimation.

4.1 Data

Our SVAR is monthly. The sample is 1973:01 to 2019:12. We exclude the last part of the sample in order use it as a validation period for the analysis that will follow. We include seven reasonably standard macroeconomic variables: (monthly) real gross domestic output, unemployment, real oil prices, the

¹²From equation (44), we see that \hat{p}_{wt}^o depends positively on the Nash wage and hiring costs, which in turn depend on firm revenues and market tightness, respectively. Contractionary monetary policy reduces both and hence reduces \hat{p}_{wt}^o .

¹³Depending on the details, a demand shock may not present the central bank with a similar conundrum since monetary policy transmits through the economy like a demand shock. By offsetting the demand shock, monetary policy can return the economy to the efficient level, depending on how closely monetary policy can mirror a demand shock.

Federal Funds rate, core PCE inflation, real wages and the Gilchrist and Zakrajšek (2012) excess bond premium. The latter we include in the SVAR to improve the fit but do not target it.

Monthly real GDP is log cumulated real GDP growth constructed by Brave-Butters-Kelley. The real oil price is the log spot West Texas Intermediate crude oil price deflated by core PCE. The real wage is measured as log average hourly earnings by production and nonsupervisory employees deflated by core PCE. Finally, the other variables are standard. Below we describe the oil and money high frequency external instruments.

4.2 Identification of the Effects of Oil and Money Shocks

Let Y_t is a $N \times 1$ vector of endogenous variables, ν_t is the corresponding vector of reduced-form residuals, B_0 is the intercept term and B_1, \dots, B_p are a set of $N \times N$ coefficient matrices. Then we start with the following reduced-form VAR(p) model which we can estimate via OLS:

$$Y_t = B_0 + B_1 Y_{t-1} + \dots + B_p Y_{t-p} + \nu_t \quad (46)$$

The reduced form residuals may in turn be expressed as functions of primitive structural shocks ε_t , as follows:

$$\nu_t = \mathcal{I} \cdot \varepsilon_t$$

where ε_t is an $N \times 1$ vector and \mathcal{I} is an $N \times N$ coefficient matrix. Let ε_{st} be the structural shock to oil and ε_{rt} the structural shock to monetary policy. We are interested in identifying the effects of these shocks on the set of reduced form residuals. Once we have estimated these effects, we can then use the VAR to trace out the dynamic effects on the economy.

To identify exogenous variation for the oil and money shocks, we use as external instruments the surprises in futures market prices constructed around OPEC and FOMC announcements, respectively. Let s_t^i be the surprise in the log price of a future contract for variable i at the announcement date t . The key assumption is that the news revealed within the window that leads to the surprise in the futures price can be treated as exogenous with respect to the other variables in the VAR. Let $\mathbb{E}_t(P_{t+h}^i)$ be the log expected spot price conditional on the information available after the announcement and $\mathbb{E}_{t-w}(P_{t+h}^i)$ be the log forecast of the same variable just prior to the window opening. Then assuming that the risk premium does not change within

the window around the announcement, the surprise simplifies to:

$$s_t^i = \mathbb{E}_t(P_{t+h}^i) - \mathbb{E}_{t-w}(P_{t+h}^i)$$

Each surprise $s_t^i \in \{s_t^o, s_t^r\}$ is used as an instrumental variable to identify a column of coefficients in the structural impact matrix \mathcal{I} . Finally, to be a valid instrument, s_t^i must satisfy the relevance and exogeneity assumptions:

$$\mathbb{E}(s_t^i \varepsilon_t^i) \neq 0$$

$$\mathbb{E}(s_t^i \varepsilon_t^j) = 0, j \neq i$$

Under these assumptions, the column of S that corresponds to each variable i is identified up to a sign and scale with:

$$\mathcal{I}_j^i = \frac{\mathbb{E}(s_t^i \nu_t^j)}{\mathbb{E}(s_t^i \nu_t^i)}, j \neq i$$

where \mathcal{I}_j^i is the two stage least squares estimate of the regression of ν_t^j on ν_t^i with s_t^i as an instrumental variable for ν_t^i . We normalize the impact of the money shock on the Fed Funds and the impact of the oil shock on the real oil price to be one standard deviation.¹⁴

To construct oil price surprises we follow Känzig 2021 exactly.¹⁵ We consider the surprise in the futures price for oil on the day in which the Organization of the Petroleum Exporting Countries (OPEC) has a meeting. The relevant time window over which the surprise takes place is between the day of the announcement and the last trading day before the OPEC meeting.¹⁶

For monetary policy surprises we start with Gertler and Karadi (2015) by using unexpected movements in interest rate futures around Federal Open Market Committee (FOMC) dates. We then follow Bauer and Swanson

¹⁴See footnote 4 in Gertler and Karadi 2015 for the details.

¹⁵For some classic approaches to identifying oil shocks, see Hamilton (1983) and Kilian (2009).

¹⁶Unfortunately intraday oil futures are not available until the latter part of the sample. As discussed by Känzig 2021, markets react to OPEC announcements slower compared to FOMC announcements, and this gives further justification for using a daily window rather than a tighter one.

(2022) by also measuring surprises around non-FOMC dates where the Federal Reserve revealed information.¹⁷ To measure the futures market surprise we use the unexpected movement in the first principal component of the first four quarterly Eurodollar future contracts. Given data availability, we are able to use a very tight window of thirty minutes: the money shock surprise is thus the log difference between the realized value twenty minutes after the announcement and the forecast ten minutes prior to the meeting. To identify contemporaneous effects of interest rate surprises, we begin in 1988:01 given that interest rates futures data are not available until then. Note that we still use the whole sample to estimate the reduced form coefficients in the VAR.

One challenge we need to address is that oil prices have predictability for interest rate surprises: an increase in the growth of oil prices prior to the FOMC meeting predicts an increase in the surprise, which appears to violate our maintained hypothesis that the surprises are exogenous. A likely explanation involves endogeneity: monetary policy tends to ease when oil prices fall and vice versa when they rise.¹⁸ Accordingly, we purge from our measure of the monetary surprise the information contained in oil prices, as follows: we run the regression of money surprises on the log change in oil spot prices calculated between the day before the meeting and the previous month, Δp_{ot} . We find that monetary policy surprises can be predicted by oil prices:¹⁹

$$s_t^r = +.073 \cdot \Delta p_{ot} + \xi_t$$

(.038)

¹⁷We also do not include the measured money shock the month of the Lehman Brothers collapse. Because the markets were expecting a larger easing, our measure shows an unanticipated tightening. At the same time, there was a huge drop in GDP and industrial production due to the financial collapse. Because factors beyond monetary policy were relevant to the drop in real activity, we thought it was prudent to drop this observation. The only effect on our VAR is that it reduces slightly the impact of a surprise tightening on real GDP.

¹⁸On the topic see for example Cieslak and Schrimpf 2019, Miranda-Agrippino and Ricco 2021, Bauer and Swanson 2021, and Bauer and Swanson 2022. One might argue that the effects of oil prices prior to FOMC dates on interest rates might be captured in futures markets. A reason why this might not be the case is uncertainty regarding the central bank's reaction function, leading financial markets to underestimate feedback effects from oil prices.

¹⁹This is in line with evidence from Bauer and Swanson 2022 who use a broader information set to purge the money shock. However, when using their measure of orthogonalized money surprises, we find a positive and significant impact of money shocks on oil prices.

We then use the residuals of this regression, $\hat{\xi}_t$, as the monetary policy surprises, giving us an instrument that is orthogonal to oil prices. We note that without this adjustment, our SVAR would predict that a surprise monetary tightening would increase oil prices, an outcome that is clearly the product of not properly controlling for the endogeneity of monetary policy.

4.3 Impulse Responses to Money and Oil Shocks

Figure (1) reports the impulse responses for the identified money and oil shocks along with ninety-five percent confidence bands.²⁰

The IRFs for the money shock are similar to previous estimates obtained in the literature: A monetary policy tightening of 15 basis points implies a decline in GDP of about 10 basis points after ten months along with a decline in the price level of about 10 basis points. Associated with the decline in output is a rise in unemployment of roughly half a percentage point. Real wages also decline slightly, though the estimate is not statistically different from zero. After forty to fifty months all the real variables have reverted to their initial values. The real oil price declines moderately but is not statistically different from zero, in line with previous evidence in the VAR literature (e.g. Soriano and Torró (2022)) as well as high-frequency evidence (e.g. Rosa (2014)).²¹

The IRFs for the oil shock behave similarly to those in Känzig 2021, though with some differences due the variables in the VAR not being identical. The oil shock has a stagflationary effect: A shock that generates a 6

²⁰Confidence bands are computed using the wild bootstrap.

²¹To test directly the high-frequency effect of money on oil prices, we construct the oil surprise exactly as above but around the FOMC date instead of the OPEC meeting date. By using the oil price surprise instead of the monthly price we control for oil price movements prior to the meeting. Let $s_t^{o,FOMC}$ be the oil surprise around the FOMC meeting and ν_t^r the reduced form innovation in the Federal Funds rate. We then estimate the regression of $s_t^{o,FOMC}$ on ν_t^r using the high frequency money surprise s_t^r as an instrument for the residual:

$$s_t^{o,FOMC} = \underset{(.16)}{-.006} - \underset{(6.67)}{1.28} \nu_t^r + \varrho_t$$

The point estimate of the coefficient is negative, implying that a monetary policy tightening reduces the price of oil on average, but the standard deviation is 6.6 and the t-stat is -.19, suggesting that the relationship between money surprises and oil surprises is not statistically different from zero. The regression is consistent with findings from Rosa (2014), that shows that the correlation between money and oil surprises in a window around FOMC meetings is negative but not significant when using a daily window.

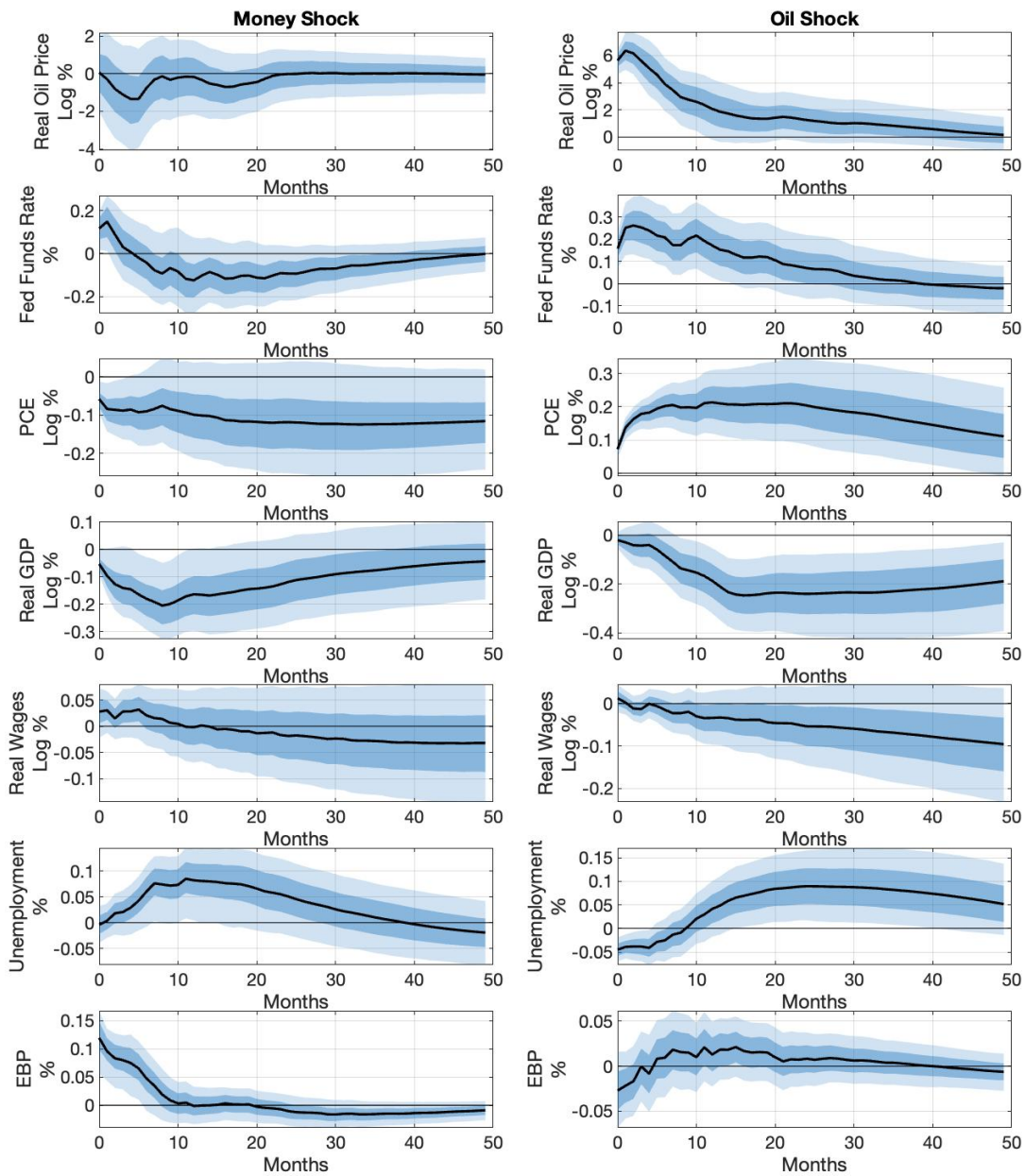


Figure 1: SVAR-based impulse responses for identified money and oil shocks. The solid line is the point estimate and the dark and light shaded areas are 68 and 95 percent confidence bands, respectively, computed using the wild bootstrap.

percent increase in the real price of oil reduces GDP roughly 20 to 30 basis points and increases the (core) price level about 20 basis points. Interestingly, we find that the Fed funds rate increases about 20 basis points on impact and persists above zero for twenty months, suggesting that the central bank reacts to the increase in inflation with a monetary policy tightening. Real wages decline persistently about 5 to 10 basis points, mainly due to nominal wages increasing by less than core inflation.

4.4 Parameter Estimation

We first calibrate a set Θ_1 of parameters and then estimate the remaining parameters in the set Θ_2 conditional on the calibrated parameters. Parameters are estimated using simulated method of moments to match the model impulse response functions with those from the SVAR with identified money and oil shocks, as portrayed in Figure (1). Impulse responses are weighted using the estimated precision. Confidence intervals for the parameters are derived using the delta method. We describe the details of the estimation procedure in Appendix A.

4.4.1 Calibrated Parameters

We begin with the parameters in Θ_1 which we calibrate to reasonably standard values. We start with conventional parameters. We choose the discount factor β to generate a steady state annual real interest of two percent. We pick the elasticity of substitution between the differentiated consumption goods η to generate a steady state gross markup of 1.3. We set the feedback coefficient on inflation in the Taylor rule to 2, a number slightly above the conventional value of 1.5 in order to compensate for the absence of the output gap in the feedback rule.²²

We next turn to the labor market parameters. We set the job survival rate ρ to a monthly value of 0.96, implying an average employment duration of two and a half years, consistent with the evidence. As noted earlier, we also choose worker’s bargaining power ς and the match elasticity σ to each equal 0.5, so that the Hosios condition is satisfied, implying that when wages are perfectly flexible and there is Nash bargaining, job creation is efficient.

²²All the results are robust to calibrating the Taylor rule parameter to 1.5. A weaker monetary response would imply an additional half percentage point of PCE inflation due to money shocks at the peak of the 2022 inflation surge (see Section 6).

Next, we choose the worker’s flow outside option b so that the ratio to the steady state contribution of the worker to the match is 0.72, consistent with Hall (2009) and implying a value of b of 0.7. Finally, we set the steady state unemployment rate equal to the sample mean of 5 percent.²³ We can then use the steady state of the labor market to pin down the cost of posting a vacancy c at 0.09.

Next we turn to oil. Consistent with the calibration in Bodenstein et al. (2012), we set the steady state ratio of oil used in production to output, o/y , and the steady ratio of firm to household expenditures on oil o/c_o to respectively 3.0 percent and 1.5 percent. The steady state ratio of oil to output pins down the share of labor in production α at 0.97.²⁴ The steady ratio of firm to household expenditures on oil pins down the share of oil in households’ expenditures χ at 2 percent.²⁵

4.4.2 Estimated Parameters

Conditional on the calibrated parameters, we then estimate nine parameters: the two parameters regulating complementarities with oil in production and consumption (ϵ and ψ), the wage rigidity parameter (γ), the habit persistence (h), the price rigidity (λ) and the persistence and volatilities of the money and oil shocks (ρ^r , ρ^o , σ^r , σ^o).

Table 1 presents the results. The estimates of ϵ and ψ , 0.37 and 0.02 respectively, suggest strong complementarities with oil in both production and consumption. Though the standard errors are large, we can reject the null of no complementarities. What is giving the high degree of complementar-

²³Blanchard et al. (2022) estimate the natural rate to be 5%.

²⁴We justify the 3 percent share of oil in production as follows: first, as in Bodenstein et al. (2012), we include natural gas along with petroleum in the measure of the oil. According to the US Energy Information Administration, petroleum and natural gas expenditures average 4.5% as a share of domestic GDP over the period 2010-2020. Finally, oil inputs in production account for about 2/3 of total oil usage, giving an estimate of the production share of 3.1% (see the next footnote).

²⁵In 2021, according to the U.S. Information Energy Administration, 67.2% of petroleum consumption is accounted for by transportation, 26.9% by industrial use, 2.8% by residential, 2.5% by commercial and 0.5% by electricity production. Transportation includes usage that can be partially attributed to the household’s sector and partially to the production sector. In particular, 63% of it is motor gasoline (including transportation for commercial purposes), 23% is distillate fuel oil and 10% is jet fuel and aviation gasoline. Splitting transportation usage in half between households and firms, this gives a division of total oil usage in 2/3 for production and 1/3 for final consumption.

Parameters Θ_1	Calibration	Parameters Θ_2	Estimate
β	.998	ϵ	.374 (.160)
η	4	ψ	.020 (.337)
ϕ_π	2	γ	.697 (.145)
ρ	.96	h	.914 (.036)
σ	.5	λ	.945 (.011)
ς	.5	ρ^r	.952 (.011)
b	.7	ρ^o	.967 (.013)
o/c_o	1.5	σ^r	.019 (.006)
o/y	.03	σ^o	.060 (.025)
u	.05		

Table 1: Values for the model parameters and steady-state targets. The first two columns report the calibrated parameters in Θ_1 , the last two columns report the estimated parameters in Θ_2 with their point estimates and standard errors in brackets.

ity in production is the sharp drop in output and increase in unemployment in response to the oil shock. With substitutability instead, the impact of the oil price shock on output would be muted as firms switch to labor and households substitute towards consumption goods. The habit formation parameter is estimated to be a monthly value of 0.91, implying a quarterly value of 0.75 which is slightly higher than estimates elsewhere.²⁶ The estimate of the monthly degree of price rigidity λ corresponds to an average duration of price stickiness of six quarters, which is inconsistent with the micro data which suggests much shorter spells. However, the model abstracts from real rigidities (e.g. Kimball) that would reduced the estimated stickiness of prices. Further, our implied estimate of the slope of the Phillips curve is in line with estimates elsewhere, suggesting that the degree of nominal stickiness we estimate is consistent with the evidence (in a reduced form sense).²⁷ The estimates also suggest considerable real wage stickiness. The estimate of the rigidity parameter γ of 0.69 implies that a change in the Nash wage from the steady state leads to a change in the actual wage of roughly one third of that amount.

²⁶The high value of h may be due to the fact that the model has consumption goods only and thus abstracts from persistence due to investment adjustment costs.

²⁷See Hazell et al. (2022).

5 Results

5.1 Model versus Data

In Figure (2) we portray the impulse response functions from the model versus those generated by the data. The left column portrays the effect of the money shock while the right side does the same for the oil shock. In each case the black line is the data along with ninety-five percent confidence intervals, while the red line is the model. Overall the fit is good: the model always stays within the confidence intervals. While the model response of output to each shock is below the point estimate from the data, the response of unemployment is on target, as are the responses of the other variables (to a reasonable degree).

5.2 Inspecting the Mechanisms: Complementarities and Tradeoffs

Two important features of model are: (i) complementarities in the use of oil for both firms and households and (ii) real wage rigidities, which introduce a short run inflation/unemployment trade-off. In this subsection we explore the quantitative implications.

For firms, in the event of an oil price shock, complementarities reduce substitution from oil to labor, enhancing the decline in labor demand. Similarly, for households complementarities reduce spending on other goods in the wake of the oil shock. Figure (3) illustrates. It presents the responses of output, unemployment and prices to an oil shock both for our benchmark model with complementarities and for the case where spending shares are constant for both households and firms (i.e. a Cobb-Douglas consumption composite in oil and goods and a Cobb-Douglas production function in oil and labor). The impact of the oil shock is dramatically larger with complementarities than without. For the benchmark model (the blue line) the peak drop in real GDP is 0.13 versus 0.04 in the Cobb-Douglas case (the red dotted line). Further, the large drop in the gap between the two cases is highly persistent. Similar results hold for unemployment. In the benchmark case the oil shock induces a persistent increase in unemployment, peaking at 0.8 about two years after the shock. Absent complementarities, the effect on unemployment is minimal.

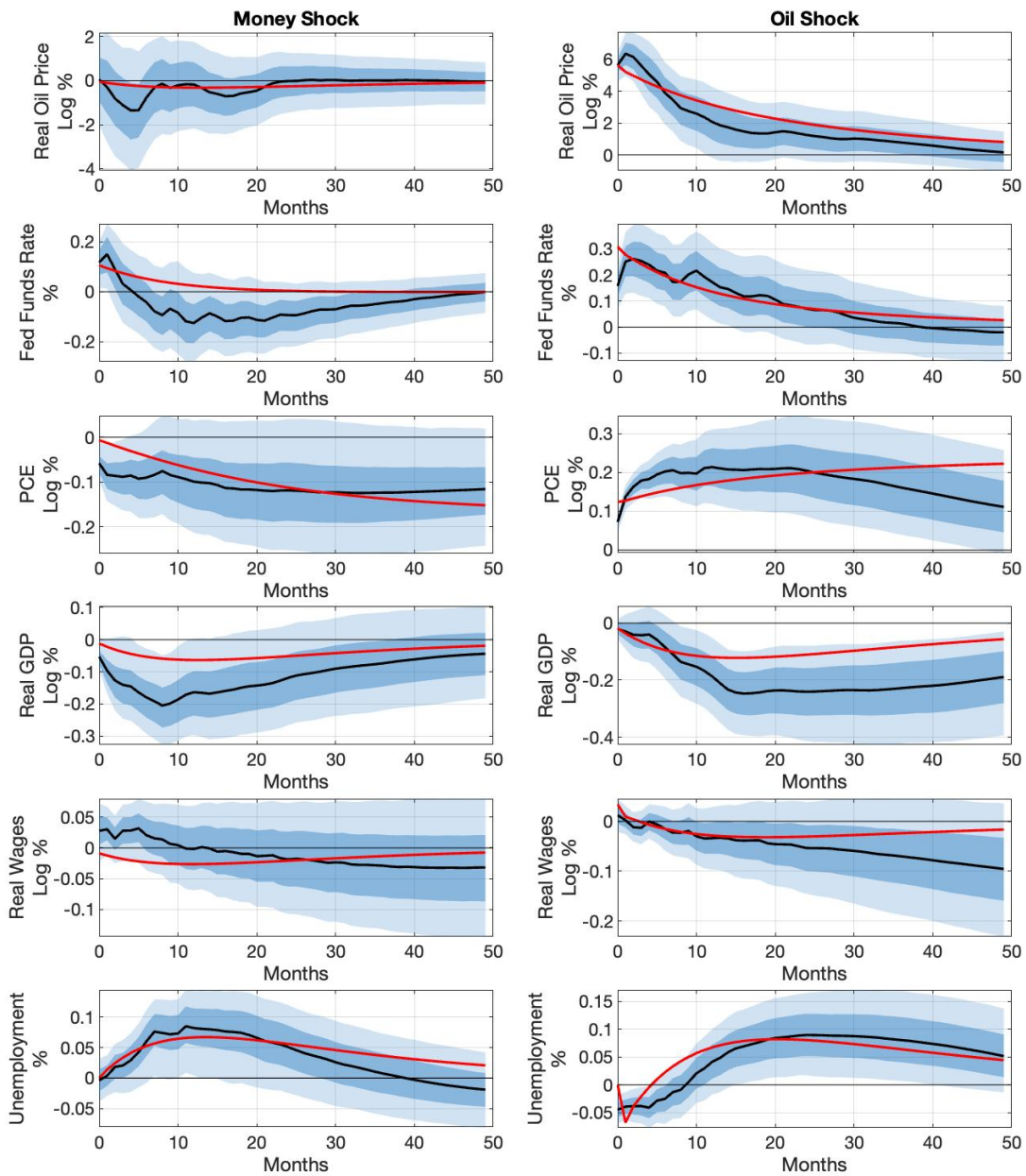


Figure 2: SVAR-based impulse responses for identified money and oil shocks vs model-based impulse responses (in red). The solid line is the point estimate and the dark and light shaded areas are 68 and 95 percent confidence bands, respectively, computed using the wild bootstrap.

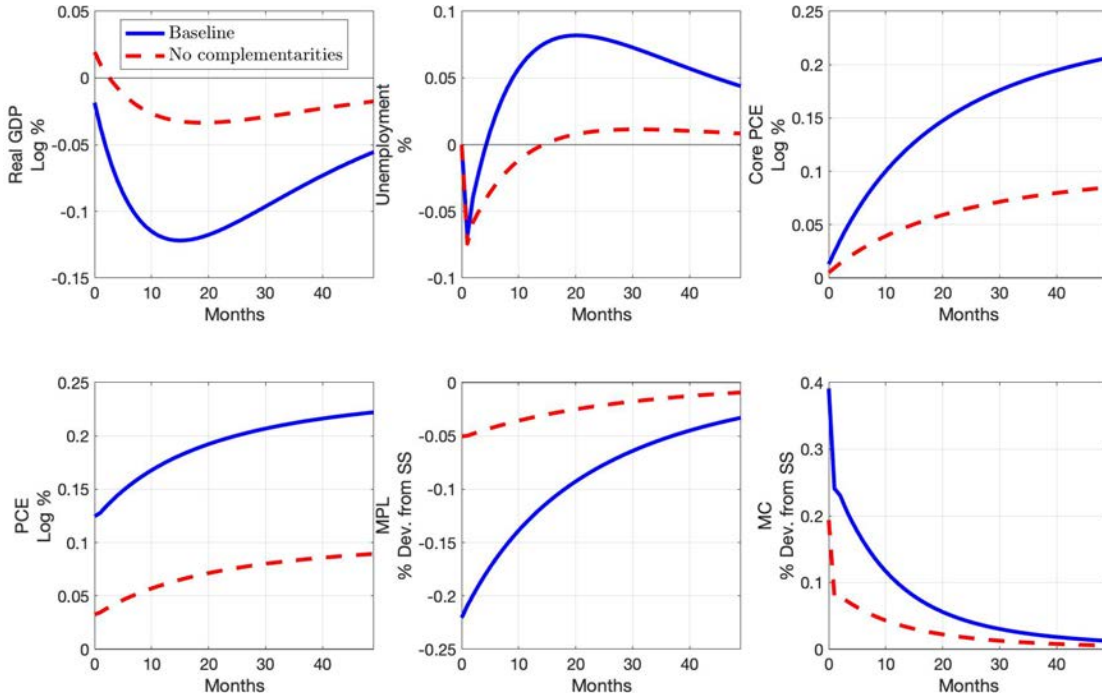


Figure 3: Impulse response functions to an oil shock. Baseline (blue) corresponds to the calibration in Table (1). The alternative (red) without complementarities has $\epsilon = 1$ and $\psi = 1$.

The oil shock also has a larger effect on nominal prices in the benchmark model than in the case without complementarities. The rise in core PCE is more than double in the benchmark model. Intuitively, the increase in marginal cost is much larger with complementarities, owing to the larger reduction in the marginal product of labor implying greater inflationary pressures. The PCE displays similar behavior, except there is a stronger initial jump in the price level since oil prices are included in the index. Finally, we confirm that complementarities enhance the decline in the marginal product of labor, which in turns enhances the impact on marginal cost. Of course it is through the enhanced impact on marginal cost that complementarities magnify the effect oil price shocks on nominal prices.

Next we examine the short run inflation/unemployment trade-off in the model. As noted earlier, absent such a trade-off it is had to rationalize why the central bank should accommodate inflationary pressures. Figure (4)

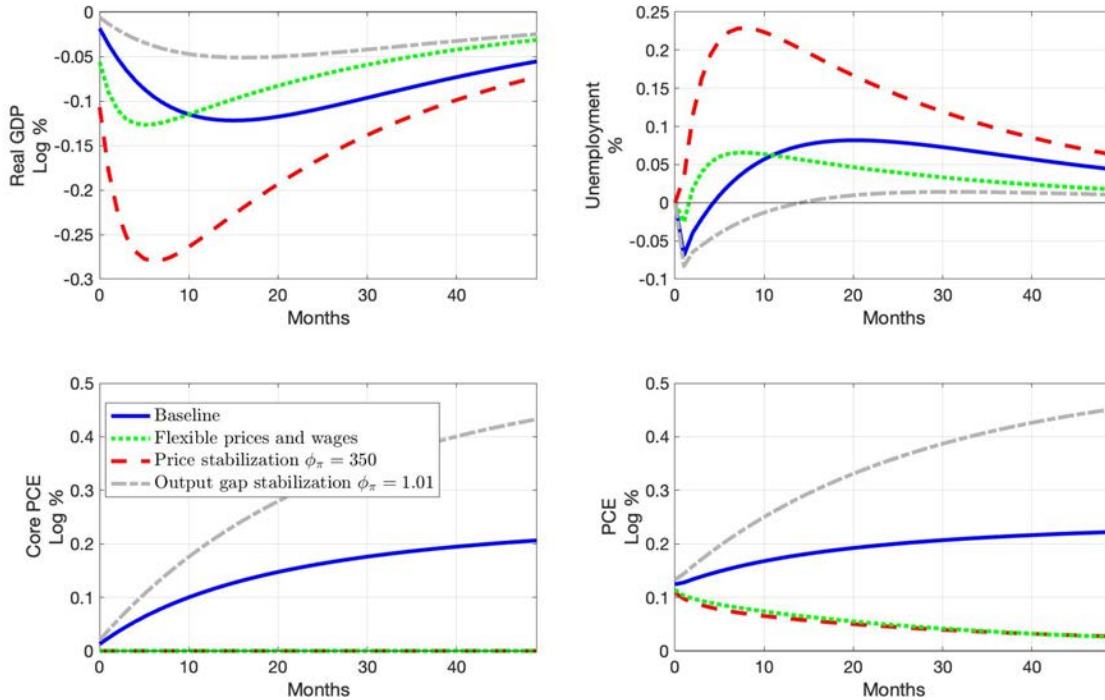


Figure 4: Impulse response functions to an oil shock. Baseline (blue) corresponds to the calibration in Table (1). Alternative 1 (green) has flexible prices and wages ($\gamma = 0$). Alternative 2 (red) is a policy counterfactual with sticky wages that stabilizes inflation ($\phi_\pi = 350$). Alternative 3 (grey) is a policy counterfactual with sticky wages that has no inflation stabilization ($\phi_\pi = 1.01$).

illustrates. To provide a benchmark, we start by analyzing the impact of the oil shock in the flexible price and flexible wage case. As in the standard NK framework, the flexible price equilibrium is a natural objective for policy makers. The dashed green lines in the top left and right panels reflect the responses of output and unemployment respectively to an oil shock for this case. There is a faster decline in output and rise in unemployment than in the benchmark case (the blue line). But the recovery is quicker. However, the peak drops in output and unemployment are similar in the two cases. Note also that the slower drop in real activity in the benchmark case generates an increase in core inflation (see the bottom left panel): Roughly speaking, in the benchmark case demand does not drop as much as supply initially (captured by the difference between the blue and green dashed line), which induces

inflationary pressures. The PCE deflator also increases in the benchmark case. Note that there is an initial jump in both cases since PCE includes energy prices.

To illustrate the inflation/unemployment trade-off we next consider a policy which stabilizes the price level. With no trade-off (or equivalently with flexible wages) output and unemployment should correspond to their efficient values (i.e. their respective flexible price equilibrium values.) On the other hand, the dashed red line gives the case with real wage rigidity. It shows that pursuing price stability induces a much larger drop in output and increase in unemployment relative to the flexible price benchmark. Over the first eight to ten months the drop in output and the rise in unemployment are more than double their respective flexible price benchmarks. Finally, we ask what happens if the central bank pursues a highly accommodating policy by setting the Taylor rule coefficient on inflation very close to unity. The policy greatly moderates the impact of the oil shock on output and unemployment, but at the cost of much higher inflation.²⁸

6 Accounting for Inflation

We now explore the extent to which the model can account for the recent increase in inflation, including the surge that occurred in mid 2021 and the persistence that has followed. To do so, we use the estimated model to perform an historical shock decomposition over the period 2010-2022 at a monthly frequency. We consider four shocks as driving forces: the demand shock ε_{bt} , the monetary policy shock ε_{rt} , the oil shock ε_{st} and the shock to match efficiency $\varepsilon_{\Phi t}$. With some qualifications, these shocks span the popular explanations for the rise in inflation. Those citing demand point to the surge in spending in 2021 due to the waning of the virus in conjunction with stimulatory fiscal policy. The case for monetary policy as a source is based on the argument that the Fed has kept rates too low relative to its norm, which can be captured by the policy shock. Oil shocks come to prominence as a potential factor, beginning with the oil price increase in 2021 that gained further impetus in 2022 as a result of the war in Ukraine. Finally, some have argued that decreases in match efficiency that tightened labor markets may

²⁸Bernanke et al. (1997) show how the monetary policy rule shapes the response to oil shocks. They show how a shift to a more accommodative policy reduces the contraction in output, but leads to a stronger positive on the price level.

also have been a supply side inflationary force. One popular factor missing is supply chain disruptions which erupted in 2021. However, these forces appear to have moderated by the end of 2021. Further, according to Di Giovanni et al. (2022), these supply chain factors accounted for only about a third of the inflation runup over this period, before giving way to other forces during 2022. Accordingly, for tractability we abstract from this factor.

We then proceed as follows. We take from the previous estimation all the parameters either calibrated or estimated. In the case of the latter, we use point estimates. We then estimate using standard Bayesian methods the standard deviations of all four shocks and also the persistence of the demand and matching shocks only, because we obtained from the earlier estimation the persistence of the money and oil shocks.²⁹ Priors are set to standard values. Details and results are reported in Table (2) in Appendix B.

To identify the persistence and standard deviations of the four shocks, we target four variables: the unemployment rate, real oil price inflation (in terms of PCE core), the Federal Funds rate and labor market tightness. Oil inflation is the quarter to quarter percent change in the real oil price; market tightness is obtained from JOLTS as the ratio between job openings and unemployed persons. From the four targeted variables, we obtain the smoothed series for the shocks using the Kalman smoother. We can then construct historical decompositions.

One complication in doing this exercise is that the oil price series displays considerable high frequency volatility, possibly due to speculation in financial markets. Some of these high frequency gyrations in oil prices do not appear to immediately translate into prices that households and firms face, as a comparison of wholesale oil prices with the PCE price index for energy would suggest. Accordingly, to clean off the speculative noise, we suppose that the PCE energy price index provides an indicator of the persistent component that is relevant to the real economy. We suppose that nominal oil price inflation ($\pi_{ot} = \ln(p_{ot}/p_{ot-1})$) equals the sum of PCE energy inflation ($\pi_{et} = \ln(p_{et}/p_{et-1})$) and an i.i.d “speculation” shock ε_{mt} , as follows:³⁰

$$\pi_{ot} = \pi_{et} + \varepsilon_{mt} \tag{47}$$

²⁹Notice that matching impulse responses pins down the standard deviation of the two shocks up to a normalization, therefore needs to be re-estimated here.

³⁰The price index becomes $p_{ct} = (\chi p_{et}^{1-\psi} + (1-\chi)p_{qt}^{1-\psi})^{\frac{1}{1-\psi}}$. That is the speculation shock ε_{mt} has no impact on real variables, or—equivalently—oil price affects the economy only through the effect on PCE energy.

The volatility of ε_{mt} (σ^m) is residually identified from the persistence of the oil shock that we previously estimated. We note that cleaning off the high frequency noise in oil prices only has a minor effect on the results: there are two data points with unusually large oil price shocks that quickly reverse. Without cleaning off the noise, the model would predict that these shocks would generate counterfactually large changes in the real economy in those two months.

Note that all nominal variables are untargeted. Accordingly, to judge how well the model captures inflation, we take the estimated model and shock processes to construct smoothed paths along with historical decompositions for the following variables: PCE inflation, core PCE inflation, nominal wage inflation and real product wage inflation. Variables are demeaned using the sample mean. Given the sample includes the slow recovery from the 2008 recession we take steady state unemployment to be 5 percent, consistent with some recent estimates of the natural rate.³¹

Finally, since parameters are estimated with data up to 2019, the end of the sample can be used for an additional validation by looking at the model-implied dynamics of both the targeted and untargeted variables.

6.1 Historical Shock Decompositions

6.1.1 Targeted Variables

Figure (5) presents a historical decomposition for the four targeted variables over the sample 2010-2022. Overall, the results are very sensible. The demand shock accounts for most of the variation in unemployment. Low demand during the slow recovery from the Great Recession contributes to higher unemployment. After that period, the demand shock reverses, helping initiate a decline in unemployment that lasts until the start of the pandemic recession. The model then treats the sharp rise in unemployment during the pandemic as largely the product of a sharp drop in demand.³² Unemployment then drops to steady state as demand improves. Interestingly, however,

³¹The sample mean over the period 2010-2022 is 6 percent. We choose to demean using 5 percent for consistency with the model calibration as well as the sample mean over the full sample. Results are robust to demeaning with 6 percent instead.

³²As we show shortly, both headline and core PCE decline during the pandemic recession, consistent with the interpretation that the demand shock is an important driving force.

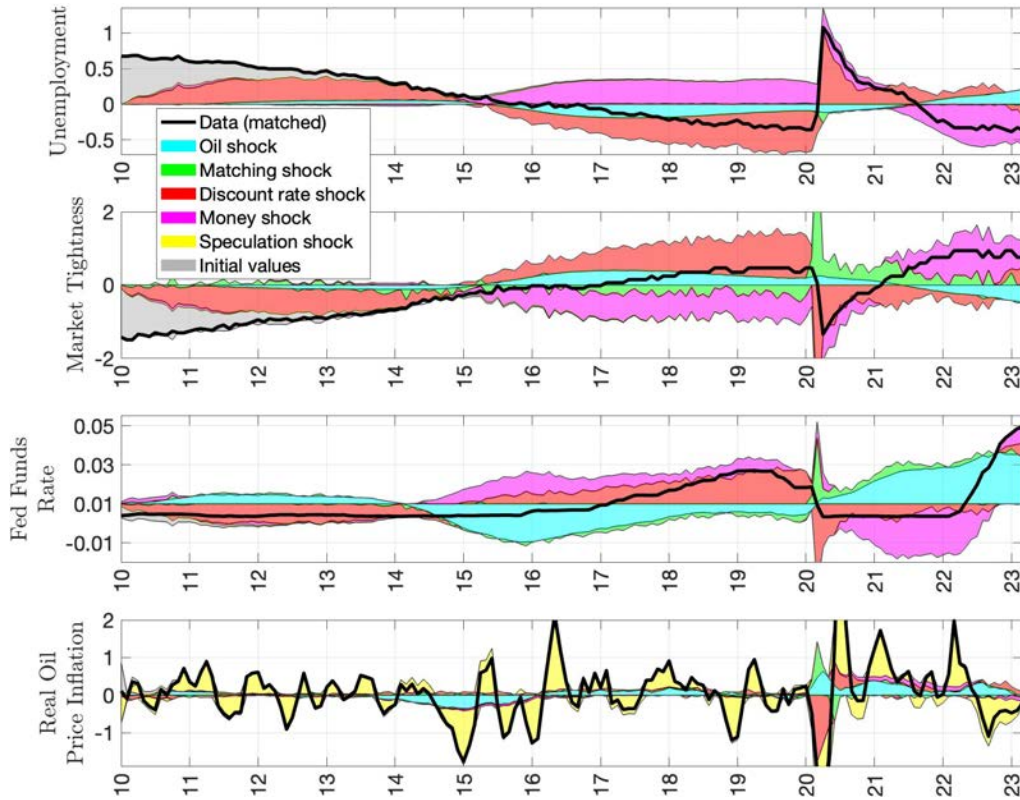


Figure 5: Historical shock decomposition of the targeted variables. Unemployment and labor market tightness are in log-deviations from the steady-state value for the model and log-deviations from sample mean for the data. The decomposition for Fed funds is computed in deviations from steady state/sample mean, and then rescaled up by the sample mean. Fed funds and oil inflation are annualized.

the drop in unemployment that continues in 2021-22 is largely the product of easy monetary policy (keeping in mind that the monetary policy works with a lag due to habit formation). Indeed, over this period, monetary policy shocks more than offsets the contractionary effect of oil shocks: From mid 2020 onward, oil shocks contribute a roughly two percentage point increase in unemployment.

The Federal Funds rate was fixed at the zero lower bound for much of the sample. The rise in the Funds rate just before the pandemic recession and the decline just after was largely in response to the rise and fall of the demand shock. From the end of 2020 to the present, easy money shocks

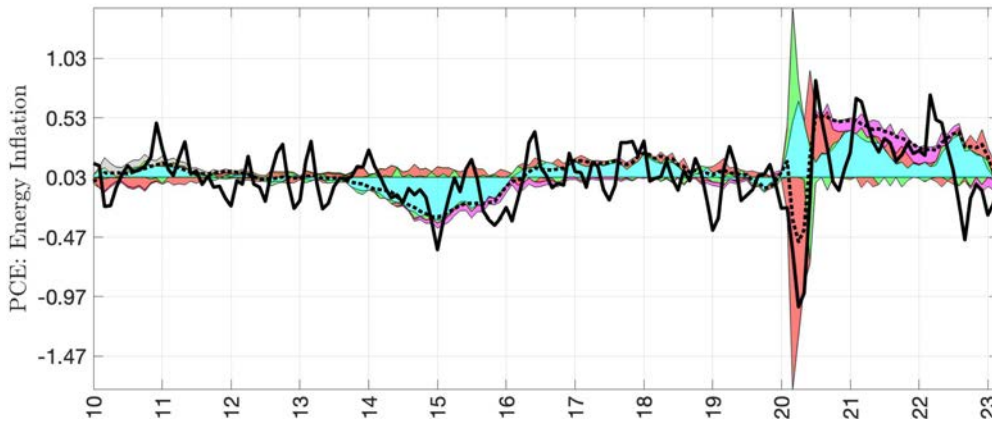


Figure 6: Historical shock decomposition of PCE energy. The decomposition is computed in deviations from steady state/sample mean, and then rescaled up by the sample mean. The inflation rate is annualized.

account for the behavior of the funds rate.

After filtering out background noise with the speculation shock (as described earlier), the oil shock mainly drives the behavior of the oil price. The one exception is that the demand shock that pushed the economy into the pandemic recession placed significant downward pressure on oil prices.

By contrast, labor market tightness is highly sensitive to the demand shock over the whole sample. The high degree of tightness in 2022 is mainly due to easy monetary policy shocks in conjunction with shocks to tightness. Interestingly, the matching shock is nontrivial during and after the pandemic but is not the leading cause of market tightness. It also does not materially contribute to unemployment variation over the sample.

Finally, as discussed earlier, we treat PCE energy inflation as the component of oil price inflation relevant to the macroeconomy. Figure (6) reports the historical decomposition of this variable. Even though it is untargeted, we track it well. As expected, most of the variation in PCE energy is due to the persistent oil shock.

6.1.2 Untargeted Variables: Inflation and Wages

Figure (7) reports the shock decomposition for headline PCE, core PCE, nominal wage growth and real wage growth.

The model tracks both PCE and core PCE over the entire sample reason-

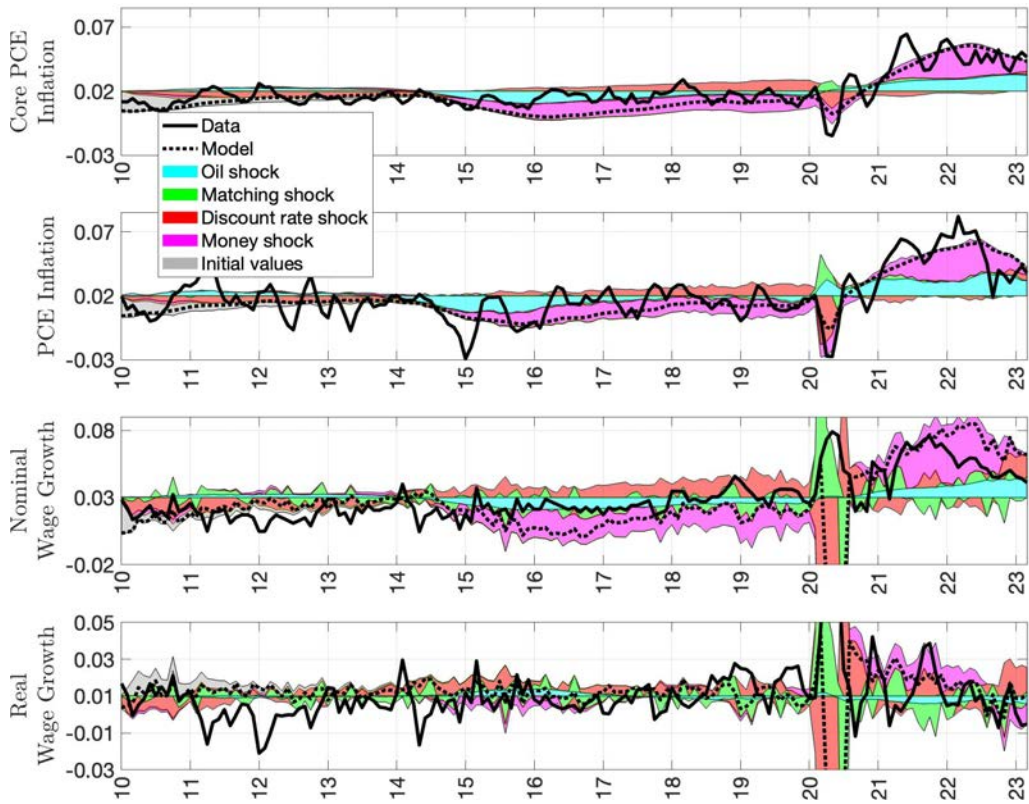


Figure 7: Historical shock decomposition of untargeted variables. The decomposition is computed in deviations from steady state/sample mean, and then rescaled up by the sample mean. All the variables are annualized.

ably well. This is true even though we do not target any nominal variables and/or add shocks to improve the fit. Note in particular that the model captures well the rise in inflation in 2021. It does miss some of the very recent decline at the end of the sample in headline PCE due largely to the drop in oil and commodity prices. But it does capture well the behavior of core inflation over the entire period. While the model does capture the upward trend in inflation in 2021, it does miss some temporary sharp upward spikes. As noted earlier, supply chain issues likely had some effect over this period.

The decompositions also resolve a puzzle as to why inflation was low during the period 2014 to 2019 despite low unemployment, while high in recent years despite the same low unemployment level. In the former period, shocks that reduced oil prices in conjunction with tight money shocks helped keep

inflation low. In the current period, just the opposite has happened: positive oil shocks in conjunction while easy money shocks have placed upward pressure on inflation. In addition, the decomposition show why, despite high oil prices in 2010 to 2012, inflation remained low: at that time low demand in the wake of the Great Recession was keeping inflation down.

Interestingly, the matching shock does not contribute significantly to current inflation, consistent with its minimal impact of unemployment. As we noted earlier, market tightness does increase significantly over this period, but just about all of the increase is an endogenous response to other shocks.³³

The model also tracks nominal and real product wage inflation reasonably well over the whole sample. There is one caveat due to a data issue, having to do with a large spike in wage inflation at the height of the pandemic recession in mid 2020 followed by a large reversal in the subsequent quarter. The likely cause of this spike was a compositional effect arising because employment losses were concentrated among low wage workers. Our model of course cannot capture this kind of compositional effect. However, outside of these two quarters the model does well.³⁴ In particular it captures the runup in nominal wages at the end of 2021 that arose along with the inflation surge. Accounting for the nominal wage surge is a combination of oil, money and demand shocks.

At the heart of the inflation surge in 2021 is a sharp increase in marginal cost. Figure (8) decomposes the rise in marginal cost into its three basic components: real wages, net hiring costs and the marginal product of labor. As the figure shows, all three components play a role. However, the decline in the marginal product of labor accounts for more than half the increase. Given its importance in the dynamics of this variable, the strong complementarity between oil and labor plays an important role in the runup of marginal cost, and hence in the runup of inflation.

³³One possibility is that our estimated persistence of the matching shock (0.548, see Table (2) in Appendix A) is too low. We checked that our results are robust to calibrating the persistence to 0.9 and 0.95.

³⁴Note also that at the height of the pandemic recession the model predicts a sharp decline in both nominal and real wages, likely due to the absence of downward nominal wage rigidity.

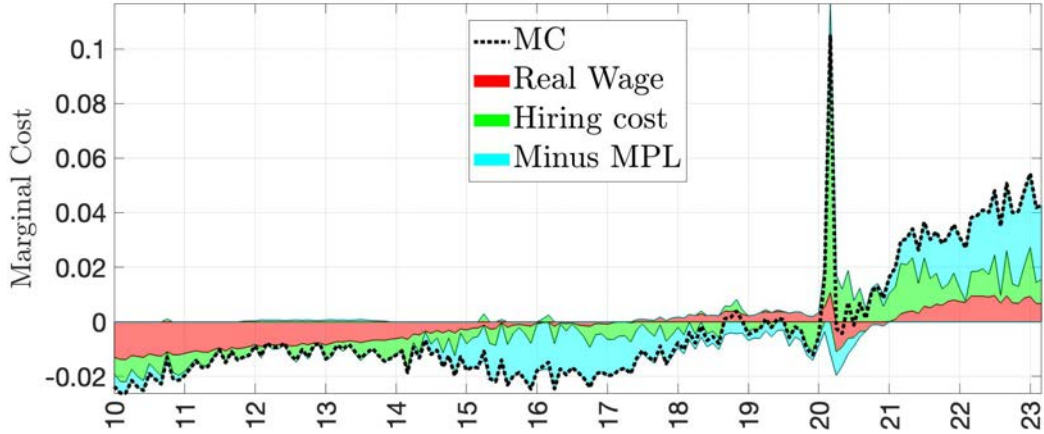


Figure 8: Historical decomposition of marginal cost into the main components from equation (40). Marginal cost is \hat{p}_{wt} , real wage is \hat{w}_{qt} (multiplied by ζ), hiring cost is $\hat{\omega}_t$ (multiplied by $(1 - \zeta)$), marginal product of labor is \hat{a}_{nt} (multiplied by minus one).

6.2 Forecasts

Finally, Figure (9) shows the forecasts of inflation and real activity conditional on a path for the Fed Funds rate and oil prices. For reasons we discussed in section 3, because real wage rigidity introduces a short run trade-off, the movement of the economy toward target inflation and unemployment will neither be quick nor painless.

In particular, we predict that, if the central bank follows the Taylor rule with a coefficient on inflation of 2, both headline and core PCE will drop to roughly three percent in about a year. Both measures will then continue to drop toward two percent at a very slow pace. There will also be a modest contraction in employment growth in the first half of the upcoming year. Unemployment will increase toward its steady state value of five percent over the year. Over the subsequent year it will overshoot by half a percentage point, as monetary policy remains tight in the response to inflation remaining above target.³⁵

The red dashed line reports an alternative scenario in which the central bank increases interest rate faster than what implied by the Taylor rule. In

³⁵The model is forecasting a slightly larger decline in oil prices a year from now than the futures market predicts: sixty dollars a barrel versus seventy. If the futures markets are correct then the model would predict somewhat higher stagflationary behavior.

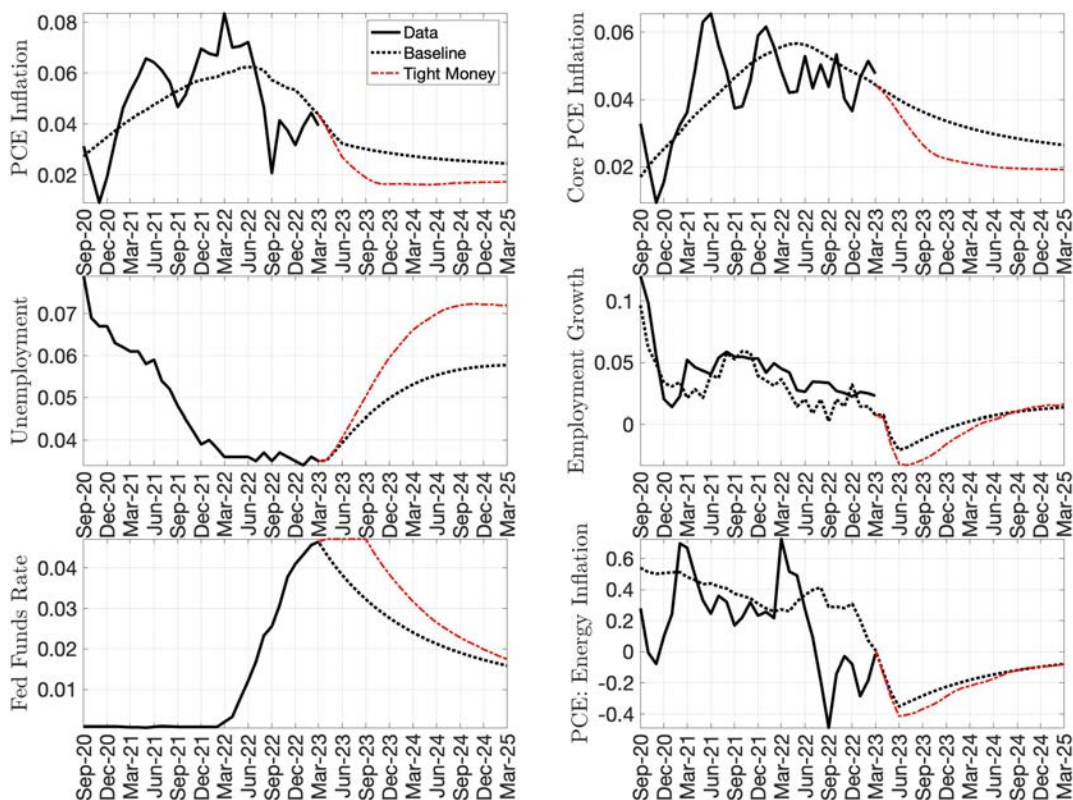


Figure 9: Forecast of selected variables. Full line is data, dotted black line is the model-implied smoothed series up to March 2023 and the mean forecast thereafter. The red dashed line is a forecast conditional on a specific path for the Fed Funds rate, which is kept fixed at 4.6% for six months starting from April 2023.

this scenario, the interest rate is higher at 4.6 percent until September 2023, and then declines progressively to steady state. Headline and core PCE decline towards two percent at a faster rate, and in particular both rates are about half a percentage point lower than the baseline scenario already in June 2023. The steeper decline in inflation comes at the cost of an additional persistent increase of unemployment of about one percent by the end of the summer, and an additional persistent decrease in employment growth of about one percent in June 2023.

In sum, under our baseline scenario there is slow convergence of inflation to target along with a “quasi” soft landing in real activity. We note two caveats. First, if the Federal Reserve pursues a tightening strategy designed

to reach the two percent target earlier, the model would predict a larger contraction in economic activity. Second, in our benchmark analysis we have assumed that despite inflation predicted to be in the three percent range over the next two years, long horizon inflation expectations remain anchored at the two percent target. If they were to increase to three percent, for example, that would complicate the central bank’s task even further.

7 Concluding Remarks

We have developed and estimated a simple New Keynesian model designed to account for the recent inflation surge. Among other things, the model features oil as a complementary good for households and as a complementarity input for firms. It also includes unemployment and real wage rigidity. We estimate the key parameters by matching model impulse response to those from identified money and oil shocks in a structural VAR. We then show that our model does a good job of explaining unemployment and inflation since 2010, including the recent inflation surge that began in mid 2021 and has lasted through early 2023.

We show that mainly accounting for this surge was a combination oil price shocks and “easy” monetary policy, even after allowing for demand shocks and shocks to labor market tightness. Important for the quantitative impact of the oil price shock is a strong production complementarity between oil and labor, in conjunction with wage rigidity. Also playing a role is the short run trade-off between unemployment and inflation that arises from real wage rigidity, which may account for the degree of central bank’s accommodation of inflation over this period. Interestingly, the model helps account for why during the period 2015 to 2019 inflation was low despite low unemployment. At work was a series of oil price declines and “tight” money shocks, the exact opposite of what occurred during the recent inflation surge.

Finally, we have presumed that long run inflation expectations have remained tightly anchored at the target. There is however some evidence from the Survey of Professional Forecasters that the ten year inflation forecast has moved to the 2.7 to 3.0 percent range. How long we can count on inflation expectations remaining anchored as inflation persists in the three percent or above range is an important topic for future research.

Appendix

A Estimation by Matching Impulse Response

In this section, we explain how the parameters are estimated and the confidence intervals are derived. In particular, we follow Hall et al. 2012 and Mertens and Ravn 2011 who propose an estimator based on the simulated method of moments and with inference based on the delta method. Specifically, let Λ^d be the $T \cdot N \cdot S$ vector of stacked impulse responses estimated in the data, where $T = 50$ is the forecast horizon in months, $N = 6$ the number of variables that are targeted, and $S = 2$ the number of shocks considered. Also, let $\Lambda^m(\Theta_2|\Theta_1)$ be the $T \cdot N \cdot S$ vector of stacked impulse responses obtained from model simulations, where Θ_2 is the set of parameters to be estimated conditional on the calibrated parameters Θ_1 . Finally, let Σ_d^{-1} be a weighting matrix. The estimator of Θ_2 is given by:

$$\hat{\Theta}_2 = \arg \min_{\Theta_2} \left[(\Lambda^d - \Lambda^m(\Theta_2|\Theta_1))' \Sigma_d^{-1} (\Lambda^d - \Lambda^m(\Theta_2|\Theta_1)) \right] \quad (48)$$

For the weighting matrix Σ_d^{-1} , we follow the standard approach to use the precision of the IRFs estimated from the VAR along the main diagonal, so that estimates with a smaller variance are assigned a larger weight in the minimization. We make an exception for the contemporaneous impact of the money shock on Fed Funds and the contemporaneous impact of the oil shock on the oil price, which we assign a larger weight to ensure these own impact moments are estimated more precisely.

The standard errors of $\hat{\Theta}_2$ are computed using an estimate of the asymptotic covariance matrix derived with the delta method:

$$\Sigma_{\Theta_2} = \Lambda_{\Theta_2} \frac{\partial \Lambda^m(\Theta_2|\Theta_1)'}{\partial \Theta_2} \Sigma_d^{-1} \Sigma_S \Sigma_d^{-1} \frac{\partial \Lambda^m(\Theta_2|\Theta_1)}{\partial \Theta_2} \Lambda_{\Theta_2} \quad (49)$$

where

$$\Lambda_{\Theta_2} = \left[\frac{\partial \Lambda^m(\Theta_2|\Theta_1)'}{\partial \Theta_2} \Sigma_d^{-1} \frac{\partial \Lambda^m(\Theta_2|\Theta_1)}{\partial \Theta_2} \right]^{-1}$$

$$\Sigma_S = \Sigma + \Sigma_s$$

and Σ denotes the covariance matrix of the estimated SVAR-based IRFs and Σ_s is the covariance matrix of the model-based impulse responses.

B Bayesian Estimation Result

We report in Table (2) the results of the Bayesian estimation of the shocks over the sample 2010-2022.

Parameter	Prior	Prior Mean	Prior stdev	Post. Mean	5%	95%
ρ^b	beta	.6	.1	.231	.173	.283
ρ^Φ	beta	.6	.1	.548	.437	.647
σ^b	invg	.15	.15	.061	.055	.067
σ^Φ	invg	.15	.15	.162	.147	.177
σ^m	invg	.15	.15	.239	.209	.270
σ^o	invg	.15	.15	.042	.036	.048
σ^r	invg	.15	.15	.039	.033	.044

Table 2: Bayesian estimation of the parameters over the sample 2010-2022.

Prior means and standard deviations are standard as in Primiceri et al. (2006). The prior standard deviations are sufficiently large to not impose serious restrictions on the parameters. The estimates imply that both the matching shock and the discount factor shock are not very persistent, with the matching shock more persistent ($\rho^\Phi = .54$ at the posterior mean) than the discount shock ($\rho^b = .23$ at the posterior mean). The estimates of the standard deviations are sensible, with the posterior means of the standard deviation for oil $\sigma^o = .04$ and money shock $\sigma^r = .04$ that are of the same order of magnitude as those estimated for the IRFs matching exercise (which were normalized to match one standard deviation of oil prices and Fed funds respectively). The mean of the standard deviation for the speculation shock $\sigma^m = .24$ is substantially larger than that of the oil shock, confirming the intuition that the speculation shock captures temporary volatility in oil prices that does not translate into a persistent effect on real variables. Finally, the posterior means for the matching shock $\sigma^\Phi = .16$ and discount factor shock $\sigma^b = .06$ are larger than both oil and money (because of the lower persistence), but of the same order of magnitude.

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