Uncertainty Shocks and Monetary Smoothness in a DSGE model

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Abstract

This paper contributes to the literature on the macroeconomic effects of uncertainty shocks. It shows that, albeit a linear BVAR estimation suggests that both output and inflation are declining in response to an uncertainty shock, NK medium-scale model cannot replicate the fall in inflation when a degree of persistence in the monetary policy is introduced as the empirical evidence suggests. Remarkably, this result is independent of the source of uncertainty, being it either real or nominal.

Keywords: Uncertainty Shocks, DSGE Model, Labor search frictions, Inflation, Bayesian VAR.

JEL codes: E12, E21, E22, E24, E31, C32

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1. Introduction

The great turmoil caused by the Great Recession has renewed the attention in macroeconomic literature on the role of uncertainty in explaining the outcomes in real aggregate variables. This literature started with the seminal work by Bernanke et al. (1988), and remained basically subdued until the Great Recession, when a flourishing bunch of papers brought the macroeconomic effects of uncertainty shocks at the top of the research agenda. Starting from Bloom (2009), most of these contributions[1] agree on the detrimental effects of uncertainty in leading agents behaviors and eventually, the fluctuations in macroeconomic aggregates. According to this literature, the surge of uncertainty during the Great Recession was one of the driver of the contractionary business-cycle co-movements among output, consumption, investment, and employment. Some contributions as Leduc and Liu (2016) go further, by arguing that uncertainty shocks depress not only real variables, but also the nominal ones, namely the inflation rate and the nominal interest rate. This paper sheds the light on the inflation response to uncertainty shocks by stressing on the role of the monetary policy rule as crucial to get insights about the dynamics of the nominal side of the economy.

The paper shows that, although the estimates of a simple linear VAR supports the downturn in both output and inflation in response to an uncertainty shock, a standard New-Keynesian medium-scale model hardly replicates the declining path of inflation to an equivalent uncertainty shock. This general equilibrium model is able to generate the fall in inflation only once it is assumed that monetary policy react immediately with no lags to the uncertainty shock. By setting instead, a smoother reaction of the monetary policy in line with the empirical evidence, the inflation responds positively to higher uncertainty in the model. Remarkably, the inflationary path is robust independently from the type of uncertainty considered, being it either real or nominal.

The literature of uncertainty shocks have shown that standard Real Business Cycle model does not capture the fall in the economic activity in response to an increase in economic uncertainty. Due to precautionary savings, higher uncertainty about the future induces agents to consume less and work more. Since technology and capital remain constant on impact, the increased hours worked foster output making the uncertainty shock eventually expansionary. Investment goes up in turn, compensating the fall in consumption on the demand side. The dynamics changes in demand-driven model as the standard Neo-Keynesian framework. When nominal frictions prevent prices to adjust freely, the lower consumption caused by the precautionary saving, effectively reduces output. This diminishes on impact the return of capital and in turn, investments fall.

[1] See for example Arellano et al. (2016), Bloom et al. (2007), Bloom et al. (2012), Bachmann and Bayer (2013), Bachmann et al. (2013), Baker et al. (2016), Basu and Bundick (2017), Caggiano et al. (2014), Fernándéz-Villaverde et al. (2011), Gilchrist et al. (2014), Nakamura et al. (2017), Schaal (2017).

The higher labor supply is not absorbed by the productive sector, but depresses the real wages. Given that prices cannot accommodate the lower demand and the fall of marginal costs, the equilibrium is restored by rising price mark-ups. The aggregate demand effect as a result of an uncertainty shock on household discount factor is described by Basu and Bundick (2017). Analogous effect is found by Leduc and Liu (2016), who study the macroeconomic response to an uncertainty shock to aggregate productivity in a Neo-Keynesian model without capital but with search and matching frictions in the labor market. Still in their framework the aggregate-demand effect prevails, but an additional option value effect linked to firms hiring decisions emerges. With search and matching frictions indeed, firms decide how many job vacancies to post by taking into account the expected value these potential jobs bring to firms. An increased uncertainty around the future might reduce the firm willingness to hire and eventually, depresses further the economic activity. Basu and Bundick (2017) and Leduc and Liu (2016) show that inflation follows the slack in real variables remaining below the steady state level for a prolonged period. Both contributions however close the model with a peculiar monetary policy rule, which is a Taylor-type rule that does not consider any smoothness over the past nominal interest rate. This paper shows that assuming that the monetary authority does not smooth the interest rate is key to obtain the decreasing dynamics of inflation in response to an uncertainty shock.

By embedding frictions in capital accumulation, labor market searching and matching and price adjustments this paper finds a bust pattern in output, consumption, investment, and employment in response to uncertainty shocks. Inflation instead, increases on impact and stays above the long-run level once the smoothness degree of the monetary policy rule is above zero, namely at 0.8, as the empirical evidence suggests.[2] The finding of a positive response of inflation to second moment shocks is not however new in the literature. Both Born and Pfeifer (2014) and Fernández-Villaverde et al. (2015) argue on the point by stressing over an upward pricing bias of firms. To avoid losses due to the too low price, firms prefer to set their prices at a higher level when the uncertainty about future outcomes is elevated. Given the decreasing marginal costs, this firm behavior translates into higher price mark-ups and inflation rate. Fernández-Villaverde et al. (2015) in particular, argue on the monetary policy specification as crucial to understand the inflation reaction to an uncertainty shock. However as others in the literature,[3] they do not deal with the persistence in the monetary policy as

[2] Just to cite few examples, Clarida et al. (1999) estimates the smoothing parameter of the Taylor rule at 0.79, Smets and Wouters (2003) at 0,95, Smets and Wouters (2007) at 0,81, Benati and Surico (2008) at 0.81, Benati and Surico (2009) at 0.74, Justiniano et al. (2010) at 0,82.

[3] Guglielminetti (2016) for instance, shows that the model by Leduc and Liu (2016) is not able to generate falling inflation in response to an aggregate productivity uncertainty shock, once decreasing marginal returns are introduced into the production function. This paper takes instead a more policy oriented perspective in explaining the different dynamics of inflation to both real and nominal uncertainty shocks.

the leading element for the inflation response. By studying the inflation dynamics at different Taylor rules calibration, this paper focuses on the role played by the inertia of the monetary rule. While increasing or decreasing respectively, the weights on inflation and output-gap simply weakens the response of inflation, by adding persistence in the monetary rule the sign of inflation response changes. Without policy persistence, the contraction in real variables caused by higher uncertainty is accompanied by a fall in inflation like it occurs after a negative aggregate demand shock. As the monetary policy reactiveness decreases, namely the smoothness parameter in the Taylor rule raises above 0,5-0,6, the inflation response to higher uncertainty is positive and looks more like a negative supply shock. These results are robust to different specifications of a standard DSGE medium-scale model, and also to considering stochastic volatility in total factor productivity as well as in the nominal interest rate. The processes leading the standard deviations are calibrated according to the estimates of a BVAR model. The empirical analysis studies in two distinct VAR specifications, the business cycle response to an innovation to a real uncertainty measure as the VXO index, and to a nominal uncertainty measure as the Monetary Policy Uncertainty index.[4]

MORE RELATED LITERATURE TO BE ADDED.

The rest of the paper proceeds as follows. Section 2. illustrates the empirical investigation about real and nominal uncertainty shocks in a BVAR framework. Section 3. builds up a Neo-Keynesian economy to study the same shocks in a theoretical model. Sections 4 describes how the non-linear model is calibrated and simulated. Section 5. discusses the impulse response functions to second moments shocks. First, it comments the aggregates response to a real uncertainty shock in a flexible prices environment, that is in a supply-driven economy. Then, it comments the impulse responses to both real and nominal uncertainty shocks when price stickiness is added, that is in a demand-driven economy. Section 6. finally concludes.

2. Empirical evidence

Before introducing the theoretical model where to study the responses of aggregate variables to real and nominal second order shocks, a preliminary analysis is provided to gauge the empirical evidence about the macroeconomic effects of higher uncertainty. A linear autoregressive multivariate model on US data is estimated via Bayesian techniques. Two VAR specifications are estimated. They differ among each other only for the measure of uncertainty considered. To get indeed evidence of the kind of shocks that are subsequently fed into the theoretical model, there are considered innovations to both real and nominal measures of uncertainty. Following Bloom (2009) among others,

[4] The VXO index is provided by the Chicago Board of Exchange, whereas the Monetary Policy index is freely downloadable from the website *http://www.policyuncertainty.com*

as a measure of real uncertainty the first specification takes the VXO index provided by the Chicago Board of Exchange. To gain instead insights about nominal uncertainty innovations, the second specification takes the Monetary Policy index (MPU henceforth).[5] For both specifications, the set of the variables is moreover completed by two real variables as i) the year-to-year changes in industrial production index (INDPRO), and ii) the civilian unemployment rate (UNRATE), and two nominal variables as iii) the year-to-year changes in the consumer price index (CPIAUCSL), and iv) the three-month Treasury bills second market rate (TB3MS).[6] Both the series controlling for the economic activity and the inflation rate are seasonally adjusted. Data are monthly for a sample interval spanning from January 1986 to July 2017. Lags of one year are considered. For the Bayesian estimation the prior used is flat, namely Normal-diffuse, while for the structural shock identification the scheme assumed is the recursive one. The ordering of the endogenous variables -uncertainty measure is ordered as first, others variables follow in the same order i)–iv) above- ensures that an innovation to the uncertainty measure, being either real or nominal, impacts all other variables at the same period it occurs. Conversely, the uncertainty index does not contemporaneously respond to innovations to others variables, but it does in the following periods according to the estimated autoregressive coefficients. The structural shocks identification makes therefore the uncertainty measures as the most exogenous among the variables considered.[7]

Figure 1 and 2.show the impulse response functions to a one standard deviation shock to respectively, VXO and MPU index. Independently from the specification considered, an innovation to the uncertainty measure triggers a contractionary dynamics in both real and nominal variables. Despite the raw series measuring real and nominal uncertainty are not very high correlated -about 0,48- the economy response to innovations affecting the former is very similar. Except for the persistence of the shock to the uncertainty measure, that is significantly lower in MPU index than in VXO index -around half of the latter at one-year horizon-, the responses of all variables are qualitatively indistinguishable. Industrial production and unemployment rate face opposite hump-shaped responses. The former initially decreases and starts to recover at around three quarters. The effects are not statistically different from zero at around two years. The effects on unemployment instead last more. Its value is still above its long-run mean after more than four years. As regards the nominal variables, both the inflation rate and the short-run interest rate react downwardly in response to an uncertainty shock. On

[5] This measure is accessible from the website *http://www.policyuncertainty.com* and is provided by implementing the same approach developed in Baker et al. (2016) to recover the Economic Policy Uncertainty index. These kind of uncertainty indeces are built up by considering different components. One of them considers the newspaper coverage of policy-related economic uncertainty.

[6] All series i)-iv) are retrieved by the FRED database.

[7] The underlying assumption of the structural shocks identification is in line with the most of contributions on macroeconomic effects of uncertainty shocks. See Caggiano et al. (2014) and Leduc and Liu (2016) among others.

impact in particular, inflation falls only after an innovation to the VXO index, whereas increases in response to an innovation to the MPU index. For the latter however, the response shortly becomes negative and eventually, result more persistent than to an innovation to the MPU index. The fall in inflation implies a monetary policy easing. The nominal interest rate contracts peaking at around one year and half in response in both specifications. Summing up, according to the BVAR analysis, a shock to either real or nominal uncertainty measures is contemporaneously contractionary and deflationary. Intuitively, in addition to the precautionary agents behavior that limits the demand for consumption and irreversible investments, the downturn in real and nominal variables is presumably worsened by the presence in the economy of nominal frictions that prevent prices from quickly adjusting.

3. DSGE model with uncertainty shocks

3.1 Environment

The following section describes the DSGE model used to simulate the real and nominal uncertainty shocks. The theoretical environment is a standard medium-scale DSGE model with the addition of search and marching frictions in the labor market. The economy is populated by households, firms and an authority that manges the monetary policy. The output of the economy is produced by using two complementary factors: labor and capital. Employing both of them implies some extra costs for the economy. For the labor, expenditure in posting vacancies make costly hiring new workers. For the capital, adjustment costs in investment and a depreciation rate dependent upon the capacity utilization make costly using capital in current and future production. Labor and capital are both employed by heterogeneous wholesale firms, each producing a different variety of intermediate goods. These intermediate goods are then collected and transformed in final goods by a representative aggregator firm. The final goods are consumed by a representative households, whose members are either employed in the wholesale sector or are unemployed and are searching for a new job. Nominal frictions are introduced as price adjustments costs in the wholesale sector. The exogenous processes are assumed to the total factor productivity and to the monetary policy rule. The source of innovations for the economy is however twofold. In addition to the shocks that hit the level of total factor productivity and nominal interest rate are not constant, still their standard deviations are assumed to be stochastic, namely subject to idiosyncratic shocks.

3.1.1 Labor market

The labor market in this model economy is featured by search and matching frictions *à* la Mortensen and Pissarides (1994). Differently from a frictionless Neoclassical labor market, to employ more labor input in the production process, firms cannot immediately demand for new workers or for more worked hours from the same workers. To do that, each wholesale firm i in the economy, with $i \in (0,1)$, have to firstly open new job vacancy positions $v_t(i)$. This activity is however costly. For each vacancy a wholesalers posts, it has to pay an amount $\frac{\kappa}{\lambda_t}$ of consumption goods, where κ is a constant term and λ_t is the marginal utility of consumption for households at time t. With a probability q_t, vacancies posted by a firm are filled by unemployed worker that were searching for a new job. On the supply side of the labor market indeed, the household members can be either employed workers or unemployed workers. The latter cannot directly offer their services to the productive sector, but they have to firstly enter into the spell of searchers for a new job u_t. With a probability p_t, worker who are searching for new jobs are hired.. In aggregate terms, at each period the flow of new jobs or matches m_t between firms and workers can be then equally given by the product between the probability of filling one unit of vacancies with the total amount of vacancies, namely $q_t \int_0^1 v_t(i)di = q_t v_t$, or the product between the probability of hiring one unit of searchers with the total amount of searchers, namely $p_t u_t$. Following Pissarides (1985) indeed, the new matches in the labor market are provided by a technology, which depends on the numbers of both vacancies and searchers. This matching function is given by the following homogenous of degree one Cobb-Douglas function,

$$m_t = \mu u_t^{\varphi} v_t^{1-\varphi} \ , \qquad (1)$$

where μ and φ respectively measure the efficiency and the elasticity of the matching function. The realized new matches represent the job positions that add to the aggregate employment level N_t in the same period. The employment level that effectively contributes to the production process in one period is determined by new and incumbent matches, which have survived to a separation shock hitting the preexisting jobs at the beginning of the same period. With probability s the employed workers N_{t-1} in the previous period, are severed and enters into the spell of unemployed workers. The law of motion of the aggregate employment level is so given by

$$N_t = (1-s)\, N_{t-1} + m_t \ . \qquad (2)$$

Since the labor force is normalized to one, the unemployment spell for the economy is defined as a residual among the workers who are not employed, namely $U_t = 1 - N_t$. However, this does not exactly corresponds to the spell of workers who are searching for a new job in the same period. The latter is given by the unemployed workers at the previous period plus the workers that were employed at the previous period, but have been severed at the beginning of the period, that is $u_t = 1 - (1-s)N_{t-1}$.

3.1.2 Households

Each household is composed by a continuum of members of measure one. These members are expected-utility maximizing and infinitely-lived agents. In equilibrium a fraction N_t of them is employed in the production function, while the complement U_t is unemployed. Following Merz (1995) and Adolfatto (1996), each household behaves as a big family insuring her member against the fluctuations in consumption. The representative household faces the following utility maximization problem,

$$\max_{\{C_t,B_t\}_{t=0}^{\infty}} E_t \sum_{t=0}^{\infty} \beta^t \left\{ \frac{(C_t - hC_{t-1})^{1-\theta}}{1-\theta} - \chi \frac{N_t^{1+\eta}}{1+\eta} \right\} , \tag{3}$$

where β is the preference discount factor, θ is the intertemporal elasticity of substitution, h is degree of internal habits in consumption, η is the inverse of the elasticity of labor supply with respect to the nominal wage. Household optimization over consumption C_t and saving in risk free nominal bond B_t, is subject to the following real period budget constraint

$$C_t + \frac{B_t}{P_t R_t} = w_t N_t + b\,(1 - N_t) + D_t + \frac{B_{t-1}}{P_t} , \tag{4}$$

where P_t is the price level, w_t is the real wage earned by employed members, b is the benefit earned by unemployed members, D_t are the real profits accrued from the productive sector, which is entirely own by households, T_t are the lump-sum taxes that finance the unemployment benefit.

The intertemporal allocative problem is solved by the first order conditions with respect to consumption and nominal bond, which respectively give the marginal utility of consumption,

$$\lambda_t = \frac{1}{C_t - hC_{t-1}} - \beta E_t \frac{h}{C_{t+1} - hC_t} , \tag{5}$$

and the standard Euler equation,

$$\frac{1}{R_t} = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_{t+1}} \right] . \tag{6}$$

Differently from the case of frictionless labor market, the labor supply households optimally choose to provide is not the one equating the real wage to the marginal rate of substitution between the consumption and leisure. With search and matching frictions in the labor market, households and intermediate firms share between each other the value added of a job position. As shown below, the value they share is a function of the surplus they respectively gain by matching each other. For households the net surplus J_t^W of having one of her member employed satisfies the following Bellman equation,

$$J_t^W = w_t - \frac{\chi N_t^{\eta}}{\lambda_t} - b + (1-s)\,\beta E_t \frac{\lambda_{t+1}}{\lambda_t} (1 - p_{t+1})\, J_{t+1}^W . \tag{7}$$

Equation (7) states that the job surplus for a worker is given by the real wage net of the labor disutility he suffers in working and of the employment benefit he loses being employed, plus an extra term that considers the continuation value for the worker of being employed. Being indeed aware of the frictions that make harder to find a job once he loses it, any worker internalizes in the surplus of a match with a firm, the value of staying employed still in the next period, or equally, of not searching a job in the next period. This continuation value for the worker is however discounted by the probability $(1 - s)$ of not being severed when the separation shock occurs at the beginning of the next period..

3.1.3 Firms

The supply side of the economy includes two sectors, although the production is effectively based in only one of them. The second sector indeed, is just an aggregator that simply combines the varieties of intermediate goods into a single homogenous final good, which is consumed by households. Any variety of intermediate goods is produced by a different wholesale firm through a production function that employs labor and capital as input factors. The heterogeneity of the intermediate goods produced allows wholesalers to be monopolistic competitive in their market. They choose the price of the variety they sell by taking as given the demand for that specific variety. However, wholesalers are assumed to face extra costs in pricing the intermediate goods, in hiring workers and investing in capital. For the first and the third activity, there are assumed some quadratic and symmetric adjustment costs in the spirit of Rotemberg (1982). For hiring workers instead, the search and matching frictions in the labor market impose to wholesalers to pay a cost for any unit of vacancy they post. The differentiated intermediate goods are bought by the final sector that operates like a representative firm in a perfect competitive market. This final firm transforms at no extra costs the intermediate goods one for one into homogenous consumption goods to be sold to households.

Wholesale sector In each period t, a continuum of measure one of different wholesalers indexed by i, with $i \in (0, 1)$, produces the intermediate goods for the economy. Any wholesaler i chooses how much labor input $N_t(i)$ and capital input $a_t(i)K_{t-1}(i)$ to employ in the production function. By holding the capital, any wholesaler decides over the raw capital $K_t(i)$ to employ in the next period and over the current degree of capacity utilization $a_t(i)$. The labor is instead rent from workers at a real wage w_t. Wholesalers are forward looking regarding the levels of production factors. They moreover choose indeed, how many vacancies $v_t(i)$ to post and resources $I_t(i)$ to invest in capital. Both vacancies and investment are costly for wholesalers. For any unit of the former, wholesalers pay a cost $\frac{\kappa}{\lambda_t}$, which is eventually rebated to households. For any unit of latter, wholesalers pay a quadratic adjustment cost defined as $\Upsilon\left(\frac{I_t(i)}{I_{t-1}(i)}\right) \equiv \frac{\phi^I}{2}\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)^2$.

By producing a specific variety of intermediate good, any wholesaler faces an individual demand $y_t(i)$, that negatively depends on the price at which it sells the variety $p_t(i)$. As shown below indeed, the individual demand for intermediate goods is optimally determined by the representative aggregator firm as $y_t(i) = \left(\frac{p_t(i)}{P_t}\right)^{-\varepsilon_p} Y_t$, where P_t and Y_t are respectively the aggregate price and output level of the economy. By operating under a monopolistic competitive market, any wholesaler fixes the price of the variety it produces by imposing a mark-up over the marginal costs it faces. However, nominal rigidities in price adjustment prevents this mark-up from being constant and only dependent on the elasticity of substitution ε_p among the varieties of intermediate goods. Following indeed a pricing scheme *à la* Rotemberg (1982), any wholesaler i sets the price $p_t(i)$ of its variety at each period by paying an adjustment cost defined as $\Gamma\left(\frac{p_t(i)}{p_{t-1}(i)}\right) Y_t$, where $\Gamma\left(\frac{p_t(i)}{p_{t-1}(i)}\right) \equiv \frac{\phi^P}{2}\left(\frac{p_t(i)}{p_{t-1}(i)} - \Pi\right)^2$ is a quadratic term depending on the current price change $\frac{p_t(i)}{p_{t-1}(i)}$ and on the gross inflation rate at the steady state Π.

Each wholesaler i faces the same optimization problem consisting in maximizing the following flow of present discount value of real profits,

$$E_t \sum_{t=0}^{\infty} \beta_t \left\{ \begin{array}{c} \frac{p_t(i)}{P_t} y_t(i) - w_t N_t \\ -\Gamma\left(\frac{p_t(i)}{p_{t-1}(i)}\right) Y_t - \left(1 + \Upsilon\left(\frac{I_t}{I_{t-1}}\right)\right) I_t - \frac{\kappa}{\lambda_t} v_t \end{array} \right\} , \tag{8}$$

where the assumption of perfect capital markets implies that intermediate firms discount the future profits at the stochastic discount factor β_t,which is defined as $\beta_t \equiv \beta E_0\left(\frac{\lambda_t}{\lambda_0}\right)$. The wholesaler maximization problem is subject to four constraints. The first one is the constant return to scale production function $y_t(i) = Z_t (N_t(i))^{\alpha} (a_t(i) K_{t-1}(i))^{1-\alpha}$, where Z_t indicates the total factor productivity and α the slope of the factor marginal productivity. With α lower than one, the production function admits decreasing marginal productivity for both labor and capital factor. The second and third constraint are respectively, the employment law of motion, $N_t(i) = (1-s) N_{t-1}(i) + q_t v_t(i)$, and the capital law of motion, $K_t(i) = (1 - \delta(a_t(i))) K_{t-1}(i) + I_t(i)$, where $\delta(a_t(i))$ is the time-varying capital depreciation rate depending on the capital utilization degree as it follows, $\delta(a_t(i)) \equiv \delta + \delta_1 (a_t(i) - a) + \frac{\delta_2}{2}(a_t(i) - a)^2$.

Given the symmetry among the wholesale firms, the subscripts i are dropped in the following first order conditions that provide the optimal firm choices,

$$J_t^F = \alpha \Lambda_t \frac{Y_{I,t}}{N_t} - w_t + (1-s)\beta E_t\left(\frac{\lambda_{t+1}}{\lambda_t}\right) J_{t+1}^F , \tag{9}$$

$$MPK_t = (1-\alpha)\Lambda_t \frac{Y_{I,t}}{a_t K_{t-1}} , \tag{10}$$

$$Q_t = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \left(a_{t+1} MPK_{t+1} + Q_{t+1} \left(1 - \delta(a_{t+1}) \right) \right) \right] , \tag{11}$$

$$Q_t \delta_t'(a_t) = MPK_t , \tag{12}$$

$$Q_t = 1 + \Upsilon \left(\frac{I_t}{I_{t-1}} \right) + \Upsilon' \left(\frac{I_t}{I_{t-1}} \right) \frac{I_t}{I_{t-1}} - \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \right) \Upsilon' \left(\frac{I_{t+1}}{I_t} \right) \left(\frac{I_{t+1}}{I_t} \right)^2 , \tag{13}$$

$$J_t^F = \frac{\kappa}{\lambda_t q_t} , \tag{14}$$

$$\begin{aligned} 0 = {} & 1 - \varepsilon_p - \phi^P \left(\Pi_t - \Pi \right) \frac{P_t}{P_{t-1}} + \\ & + \varepsilon_p \Lambda_t + \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{Y_{t+1}}{Y_t} \phi^P \left(\Pi_{t+1} - \Pi \right) \frac{P_{t+1}}{P_t} \right] , \end{aligned} \tag{15}$$

$$\begin{aligned} 0 \;=\; & 1 - \varepsilon_p \left(1 - \frac{\phi^P}{2} \left(\Pi_t - \Pi \right)^2 \right) - \phi^P \left(\Pi_t - \Pi \right) \frac{P_t}{P_{t-1}} + \\ & + \varepsilon_p \Lambda_t + \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{Y_{t+1}}{Y_t} \phi^P \left(\Pi_{t+1} - \Pi \right) \frac{P_{t+1}}{P_t} \right] , \end{aligned}$$

where $Y_{I,t}$ is the quantity of intermediate goods produced by each wholesalers, while Λ_t, J_t^F, Q_t are the Lagrangian multipliers associated to respectively, production function, employment law of motion and capital law of motion.

The first order condition with respect to employment gives the Bellman equation (9), which determines the wholesaler surplus J_t^F of being matched with a worker. Analogously to the Bellman equation (7) for the workers, equation (9) states that with search frictions in the labor market, firms get an extra continuation value from matching with the workers. This gain adds to the value of marginal labor productivity net of the real wage, and makes the surplus J_t^F positive. The continuation value of a job position for wholesalers is given by the surplus they gain in the next period once that position is preserved with probability $(1 - s)$. Alternatively, from the job creation condition (14) that equates benefits and costs for wholesalers of matching with a worker, the continuation value is given by the cost wholesalers save to pay with the same probability, for posting a new vacancy in the next period.

The first order conditions (10)-(13) provide the optimal firm decisions about the capital factor. Equations (11) and (13) describes the Tobin's Q as respectively, the expected benefit and the current cost of one unit of investment. The first is given by the marginal product and the continuation value of a unit of future capital, the second by the expenditure needed to one unit of investment and the relative adjustment costs. Equation (10) delivers the marginal productivity of a unit of effective capital employed in the production function, that is of a unit of raw capital at a given degree of utilization a_t. If wholesalers did not hold the capital but they had to rent it, the equation (10) would give the rental rate that firm should pay for the capital. According to equation (12), this rental rate would equate the depreciation of the capital, that depends on its degree of utilization.

At the state steady, the capital utilization is however assumed to be full, namely one, and the investment adjustment costs results null. It derives that, the economy simplifies at the steady state as follows. From equation (13), the Tobin's Q collapses to one, from equation (11), the net return of capital equals the inverse of the stochastic discount factor, and from equation (12), the marginal productivity of effective capital is given by δ_1.

Finally, the optimal solution with respect to the individual price any wholesalers set delivers the standard Neo-Keynesian Phillips curve (15), that relates the real marginal costs Λ_t to current and future gross inflation rate, i.e. Π_t and Π_{t+1}. The Lagrangian multiplier Λ_t can be read indeed as the marginal real revenue for wholesalers, which in equilibrium must be equal to the real marginal cost that firms face.

Aggregator sector The aggregator sector is composed by a continuum of measure one of identical firms that in each period, buy all varieties of intermediate goods from wholesalers and transform them without extra costs, into homogenous final goods they sell to households in a perfect competitive market. These final goods are defined with a Dixit-Stiglitz index of intermediate goods varieties, as $Y_t \equiv \left(\int_0^1 y_t\left(i\right)^{\frac{\varepsilon_p - 1}{\varepsilon_p}} di \right)^{\frac{\varepsilon_p}{\varepsilon_p - 1}}$, where ε_p is the higher than one elasticity of substitution among the varieties. By taking the composite goods Y_t as a constraint, the representative aggregator firm optimally allocates its demand among the differentiated intermediate goods. For any variety i, the optimal demand is $y_t(i) = \left(\frac{p_t(i)}{P_t} \right)^{-\varepsilon_p} Y_t$. From the variety-specific demands it is possible to recover the aggregate price, namely the Dixit-Stiglitz price index, as $P_t = \left(\int_0^1 p_t\left(i\right)^{1-\varepsilon_p} di \right)^{\frac{1}{1-\varepsilon_p}}$.

3.1.4 Wage bargaining

The real wage at which wholesalers remunerate a unit of labor input does not equate as in a Neoclassical style labor market, the marginal productivity to the marginal disutility of that unit. In this set-up, the real wage is negotiated among firms and workers through a bargaining scheme *à la* Nash (1952). The two counterparts share the overall surplus of an active job position, that is of a match between each other. Under a standard Nash bargaining scheme, firms and workers choose the wage that maximizes a Cobb-Douglas function with arguments the corresponding net surplus J_t^F and J_t^W of having a job.

They optimize over the real wage the following,

$$\left(J_t^F\right)^{1-\omega}\left(J_t^W\right)^{\omega} \ , \tag{16}$$

where ω determines the relative weight of worker net job surplus in the Nash product (16). The first order condition gives the following optimal solution,

$$(1-\omega)\, J_t^W = \omega J_t^F \ . \tag{17}$$

Plugging then the two job surplus (7) and (9) and the job creation condition (14) into the Nash solution (17), the optimal bargaining real wage w_t^{NB} figures as follows,

$$w_t^{NB} = \omega\left(\alpha\Lambda_t \frac{Y_{I,t}}{N_t} + (1-s)\,\beta E_t \frac{\lambda_{t+1}}{\lambda_t}\frac{p_{t+1}}{q_{t+1}}\frac{\kappa}{\lambda_{t+1}}\right) + (1-\omega)\left(\frac{\chi N_t^{\eta}}{\lambda_t} - b\right) \ . \tag{18}$$

The Nash bargaining wage is a weighted average between the benefit a firm gets from a job and the cost a worker faces from the same job. Both firm benefit and worker costs are twofold. The former includes the current marginal product of a unit of labor plus the expected saving the firm gets in not posting a vacancy in the next period. This expected saving depends on both the probability of preserving the job $(1-s)$ and the future degree of tightness in the labor market, given by the ratio of job finding probability over vacancy filling probability. The worker cost of having a job is instead given by the marginal rate of substitution between consumption and leisure net of the unemployment benefit.

In each period, the degree of tightness θ_t^m in the labor market is equivalently given by the ratio between vacancies and searchers or by the ratio between the probabilities of finding a job or filling a vacancy, namely $\theta_t^m = \frac{v_t}{u_t} = \frac{p_t}{q_t}$.

Following the literature that emphasizes the importance of adding wage rigidities to make the dynamics of a model featured by search and matching in the labor market comparable with the data,[8] some inertia is introduced into the real wage adjustments. As in Hall (2005), the current level of real wage is a function of the current Nash bargaining level and of the level prevailing in the previous period as follows,

$$w_t = (w_{t-1})^{\gamma}\left(w_t^{NB}\right)^{1-\gamma} \ , \tag{19}$$

where the coefficient γ determines the inertia degree in real wage adjustments.

3.1.5 Aggregation

From the symmetry in equilibrium, it derives that the total employment evolves according to $N_t = (1-s)\,N_{t-1} + q_t v_t$ and the total capital evolves according to $K_t =$

[8] See Hall (2005) and Shimer (2005) among others.

$(1-\delta(a_t))K_{t-1}+I_t$. In aggregate terms, the amount of final goods equals the amount of intermediate goods, which is in turn the output of the aggregate the production function $Y_t = Z_t N_t^{\alpha}(a_t K_{t-1})^{1-\alpha}$. By considering aggregate output and aggregate production factors, the resource constraint of the economy is recovered by aggregating the period budget constraint of the representative household (4). Given that the net supply of risk-free bonds is null, namely $B_t = B_{t-1} = 0$, and the vacancy costs paid by wholesalers are rebated to households, the resource constraint reduces to the following equation,

$$C_t = \left(1-\Gamma\left(\frac{P_t}{P_{t-1}}\right)\right)Y_t - \left(1+\Upsilon\left(\frac{I_t}{I_{t-1}}\right)\right)I_t \ . \tag{20}$$

The resource constraint (**??**) reads the aggregate consumption at time t as a residual of the final output Y_t less the investment and the adjustment costs for changing the levels of prices and investment.

3.1.6 Exogenous processes

Exogenous dynamics of the economy is driven by the processes leading the total factor productivity Z_t and the nominal interest rate R_t. Both level and volatility of two variables are led by autoregressive processes as follows,

$$\log\left(\frac{Z_t}{Z}\right) = \rho_Z \log\left(\frac{Z_{t-1}}{Z}\right) + \sigma_{Z,t}\varepsilon_t^Z \ , \tag{21}$$

$$\log\left(\frac{\sigma_{Z,t}}{\sigma_Z}\right) = \rho_{\sigma_Z} \log\left(\frac{\sigma_{Z,t-1}}{\sigma_Z}\right) + \sigma_{\sigma_Z}\varepsilon_t^{\sigma^Z} \ , \tag{22}$$

and

$$\log\left(\frac{R_t}{R}\right) = \rho_R \log\left(\frac{R_{t-1}}{R}\right) + (1-\rho_R)\left(\rho_\Pi\left(\frac{\Pi_t}{\Pi}\right) + \rho_Y\left(\frac{Y_t}{Y}\right)\right) + \sigma_{R,t}\varepsilon_t^R \tag{23}$$

$$\log\left(\frac{\sigma_{R,t}}{\sigma^R}\right) = \rho_{\sigma_R} \log\left(\frac{\sigma_{R,t-1}}{\sigma^R}\right) + \sigma_{\sigma_R}\varepsilon_t^{\sigma^R} \ , \tag{24}$$

where $\varepsilon_t = \left[\varepsilon_t^Z, \varepsilon_t^{\sigma^Z}, \varepsilon_t^R, \varepsilon_t^{\sigma^R}\right]'$ is the vector including the independent zero mean and unit variance innovations to first and second moment of total factor productivity and nominal interest rate. The vector $\left[\rho_Z, \rho_{\sigma_Z}, \rho_R, \rho_{\sigma_R}\right]'$ indicates instead, the persistence degree of the autoregressive component of the above processes. According to equations (21) and (23), the level of total factor productivity is determined by an AR(1) process, while the level of nominal interest rate is determined by a standard Taylor rule. The monetary authority set the nominal interest rate in response to fluctuations of gross inflation rate Π_t and final output Y_t. The weights determining the nominal interest rate response to inflation and output changes are respectively given by ρ_Π and ρ_Y. Equations (22) and (24) introduce heteroskedacity in the processes leading total factor productivity and nominal interest rate. The second order shocks $\varepsilon_t^{\sigma^Z}$ and $\varepsilon_t^{\sigma^R}$ affect directly the variability of productivity and nominal interest rate and then, the one of the aggregate variables. By increasing the dispersion of possible future realizations of productivity and monetary policy, these shocks add uncertainty to the expected outcomes of real and nominal variables. For this reason, the innovations $\varepsilon_t^{\sigma^Z}$ and $\varepsilon_t^{\sigma^R}$ are conveniently named as real and nominal uncertainty shocks in the rest of the paper. [9]

3.2 Calibration

The model calibration -reported in Table 1- is standard according to the literature. It takes US quarterly data as the benchmark. The preference discount factor β is $0,992$ ensuring an annual net nominal rate around 3%. Given a log-linear specification for households utility in consumption, the intertemporal elasticity of substitution θ is fixed to 1. Still the inverse of the Frisch elasticity η is set to 1. In model simulations considering internal habits in consumption, the parameter h is fixed to $0,6$, as in Leduc and Liu (2016).

The labor share in the production function equals to $0,66$. The coefficient governing the investment adjustment costs ϕ^I is calibrated to 2.48, as in Christiano et al. (2005). In the capital depreciation function $\delta(a_t)$, the steady state degree of capital utilization a is set to 1, therefore it holds $\delta(a) = \delta$, $\delta'(a) = \delta_1$, $\delta''(a)) = \delta_2$. The parameter δ_1 of the depreciation function is recovered by the steady state relations as a function of the marginal productivity of capital. The parameter δ is set to $0,025$ -implying an annual depreciation rate of 10% in the long-run-, while δ_2 is set to one tenth of δ_1, as in Christiano et al. (2005). Regarding the level of aggregate productivity, its steady state value Z is fixed to 1 and its persistence $\rho_Z = 0,9$, as in King, Plosser,and Rebelo (1988).

By abstracting from labor force participation decisions and normalizing the population to 1, both the set of unmatched workers U in the steady state and the exogenous separation rate are assumed to $0,1$, in line with den Haan et al. (2000). As Cogley and Quadrini (1999) and den Haan et al. (2000), the vacancy filling probability is fixed to $0,7$. The elasticity of matches to vacancies φ and the worker bargaining power ω are both set to $0,5$, so that the Hosios (1990) efficiency condition holds. The real wage indexation coefficient γ is set to $0,8$ as in Leduc and Liu (2016). The total vacancy expenditure on aggregate output is calibrated at 2% as in Leduc and Liu (2016), slightly higher than in Hairault (2002) and Blanchard and Galì (2010). Following Hall and Milgrome (2008), the unemployment benefit b is set to $0,25$, so that it corresponds to about

[9] As a technical note, the log-specification of the processes (21) and (23) leading the levels of aggregate productivity and nominal interest rate, guarantees that the second order shocks enter positively into the equations even when the volatility realizations are negative.

one fourth of the wage.

The elasticity among the varieties of intermediate goods is 10 ensuring a steady state price mark-up of 1, 1. The coefficient governing the price adjustment costs ϕ^P is calibrated at 110. The coefficient implies in a linearized version of the Phillips curve, a not-resetting probability in a pricing scheme *à la* Calvo of about 0, 75.[10] The steady state level of gross price inflation is set to 1, 005, that guarantees a yearly net inflation of 2%. As regards the Taylor rule, the calibration changes according to the different model specifications. The benchmark calibration considers standard values in the literature as 0, 8 for the smoothness degree ρ_R, 1, 5 for the inflation weight ρ_Π, 0, 125 for the output-gap weight.

As regards the volatility processes, the calibration follows the empirical evidence of Section 2. The impact responses of VXO index and MPU index to the corresponding one standard deviation shocks are of respectively, 17, 6 and 47, 5 percentage deviation from the unconditional mean values.[11] Given that the long-run standard deviations of aggregate productivity and nominal interest first order shocks are conveniently fixed to 1 percent, the volatility coefficients σ_{σ_Z} and σ_{σ_R} are calibrated at 0, 1759 and 0, 4752. Albeit the shock to the real uncertainty measure is lower in magnitude, it is however more persistent than the shock to the nominal uncertainty measure. More precisely, after twelve months from the impact the effects of the former have been absorbed for around the 80 percent, while the effects of the latter for more than 99 percent. Once having transformed these values into quarterly data, the one-lag persistence coefficient of real uncertainty shock ρ_{σ_Z} corresponds to 0, 6817, while the one-lag persistence coefficient of nominal uncertainty shock ρ_{σ_R} to 0, 3759

3.3 Solution

Following Fernández-Villaverde et al. (2011), the model is solved at the third-order approximation.[12] At lower orders of approximation indeed, volatility shocks either do not enter into the policy functions -at first order approximation- or enter as cross-products with other state variables -at second-order approximation-. Volatility shocks enter independently only in third-order approximated policy functions, allowing to study the

[10] As widely used in the literature, the comparison between linearized Phillips curves under respectively, Calvo and Rotemberg pricing schemes has to be considered by neglecting the decreasing returns to scale in the production function.

[11] On impact, the VXO index increases at 3, 56 points over the unconditional mean of 20, 25, this corresponds to a variation of around 17, 6 percentage points. The MPU index instead increases at 41, 18 points over the unconditional mean of 86, 67, this corresponds to a variation of around 47, 5 percentage points.

[12] The rational expectations solution of the model is computed by using the Dynare software package developed by Adjemian et al.(2011). This solution is found by using third-order Taylor series approximation around the deterministic steady state of the model.

effects of second moment shocks holding constant the levels of other variables. However, since the solution of the model at an order of approximation higher than one, implies that the ergodic means of the endogenous variables are different from the deterministic steady state values, the impulse response functions are computed in deviations from the stochastic steady state.[13] The stochastic steady state is the fixed point at which the endogenous variables converge after having set to zero the exogenous shocks and simulated the model for a sufficient number of periods. Then, a deterministic simulation of the model is run to get the level of the endogenous variables after a volatility shock. The impulse responses functions are finally calculated by subtracting the stochastic steady state values from these levels.

3.4 Impulse Response Functions

This section comments the dynamic responses of the model to real and nominal uncertainty shocks. The analysis initially focuses on the responses to a shock increasing the uncertainty about the total factor productivity. The dynamics of the economy is studied under both flexible and sticky prices. Considering both the cases allows to gain the importance of introducing nominal rigidities in this kind of theoretical model, to make uncertainty shocks contractionary in output as the data predicts. By adding nominal rigidities does not guarantee however an analogous drop in inflation. The inflation falls as the empirical analysis of Section 2 only under very low degrees of persistence in the monetary policy. Similar conclusions are subsequently found when the analysis focuses the economy response to a nominal uncertainty shock, that is to a shock that increases the volatility of the monetary policy rate. Given its nominal nature, this kind of shock is studied only under model specifications with sticky prices. Remarkably, a sufficient degree of monetary policy persistence is crucial not only to make inflation increasing after the nominal uncertainty shock, but more generally, to make the responses of aggregate variables not negligible as they would be without inertia in monetary policy.

3.4.1 Real uncertainty shocks

Figures 2.-4. show the dynamics of main aggregate variables after a second order shock to the total factor productivity. The impulse responses functions refers to different specifications of the DSGE medium-scale model with search and matching frictions described in Section 3.1. All model specifications in the Figures 2.-4 include capital and search frictions. In addition to a version of the model that just consider these two in the model, other specifications take consumption habits and sticky real wages, both separately and jointly. Figure 2. shows the impulse response functions under the case of flexible prices, while Figure 3. and 4. under the case of sticky prices. Model

[13] For more details see Fernández-Villaverde et al. (2011), Basu and Bundick (2017).

specifications in Figure 3. and 4. only differ for the calibration of the monetary policy smoothness degree. Figure 3. shows the dynamics of the model when the coefficient ρ_R is set to zero, while Figure 4. when ρ_R is fixed to $0,8$.

Before to comment the dynamics of the aggregate variables, it is worth to highlight that the magnitude of the responses to a real uncertainty shock is sensibly different under flexible and sticky prices. According to the simulations, when the economy is not featured by nominal rigidities in price adjustment, the reaction to higher uncertainty is much weaker than when these rigidities hold. It follows that when the aggregate demand channel is muted, the precautionary channel *per se* , is not able to trigger a strong reaction in the real economy. Differently, when nominal rigidities in price adjustments are introduced and the economy becomes demand-driven, the combination of aggregate demand effects and precautionary motive effects make generates much higher effects for the aggregate variables.

Case of flexible prices Figure 2. shows that the shock to the volatility of aggregate productivity is actually contractionary in output for all model specifications that include some degree of persistence in real wage adjustment or in consumption habits. Only for the simplest specification with neither sticky real wages nor consumption habits, output raises on impact and remains above the long-run level for several periods. In the latter case indeed, consumption falls less than how investment increases. Aggregate demand responds then positively. Firms can satisfy higher demand by employing more labor and capital. On impact however, the capital stock is given and firms can increase the production only by absorbing the higher labor supply. For this simplest specification indeed, unemployment drops.

Conversely, unemployment surges in the two model specifications with rigid real wages. For these specifications, the wage stickiness compromises the surplus of having a match with a worker. As Leduc and Liu (2016) argue, an option value limiting the firm willingness in hiring might prevails in a model with search and matching frictions. When firms face long-term job relations as in this model, firms decide to hire according to the expected surplus they gain from the job relation. Albeit the lower real interest rate discounts less the future surplus and makes larger the continuation value, the current surplus falls more when wages are stuck and cannot freely accommodate the uncertainty shock. Overall, the job surplus for firms reduces. As an implication, firms post less vacancies and new matches decline as well.

Case of sticky prices By introducing rigidities in price adjustment, the recession occurring after a volatility shock to aggregate productivity is more evident. This is true independently from the reactiveness of the monetary policy, as Figures 3. and 4. well show. With respect to the case of flexible prices, the responses of real variables are more sizeable -around one order of magnitude higher- and less heterogenous among the different model specifications. Facing more uncertainty about the future outcomes, households desire to consume less, i.e. *precautionary saving effect*, and work more, i.e. *precautionary working effect*. When the economy is demand-driven however, the aggregate demand channel prevails. Higher desired saving does not translate however into higher investment, but rather depresses the economy, so that aggregate saving actually decreases. Falling output required firms to employ less inputs into the production process. Both labor and capital indeed decrease accordingly. The fall in labor is mirrored by the slump in new job matches, while the fall in capital by the drop in investment. In addition for labor input, the option value faced by firms further contracts the job surplus and the vacancies. Real prices in the markets decrease as well. Real wage and real interest rate are pushed down by the excess of labor supply and saving. Real marginal costs reduce following the overall contraction in the real economy. Under a pricing scheme *à la* Rotemberg , the real marginal costs corresponds to the inverse of the gross price mark-ups. As the plots at the bottom on the left in Figure 3. and 4. show, the firms mark-ups rise after the uncertainty shock because nominal rigidities prevent prices from plunging as the realized marginal costs. Higher mark-ups are then a consequence of the *aggregate demand effect* of the uncertainty shock. On that, Fernández-Villaverde et al. (2015) also point to a upward pricing bias of firms in responses to higher uncertainty. The precautionary behavior of firms that face a concave profit function induce them to keep prices higher, or equivalently, to raise mark-ups.

The overall effects of higher mark-ups on inflation is however dependent on the monetary policy. This is easy to capture by comparing model simulations of Figure 3. where monetary policy rule persistence is null, namely $\rho_R = 0$, to model simulations of Figure 4, monetary policy rule persistence is positive, namely $\rho_R = 0,8$. In Figure 3. the inflation response to an uncertainty shock is overall negative. Although for the two specifications with non-zero habits in consumption, inflation reacts positively on impact, it promptly reverts back and remains persistently below the steady state until the shock effects fade away. In accordance with the fall in inflation, when monetary authority is ready to intervene without lags, the nominal interest rate decreases to alleviate the downturn. The finding corroborates the results of Leduc and Liu (2016) and Basu and Bundick (2017), that do not admit inertia in monetary policy as well. Under different DSGE models than encompass search frictions but not capital, i.e. Leduc and Liu (2016), and capital but not search frictions, i.e. Basu and Bundick (2017), both find a decreasing inflation to uncertainty shocks.[14]

The inflation response totally changes becoming positive, when inertia in monetary policy is introduced. By looking at the plots in Figure 4., it is easy to note that inflation and nominal interest rate are the only variables, whose dynamics change the sign with respect to the case of no smoothness in monetary policy. Real variables conversely, do not

[14] Leduc and Liu (2016) consider a second order shock to the total factor productivity, while Basu and Bundick (2017) to the preference discount factor.

change the sign of their responses. The recession in output, consumption, investment and employment is confirmed, but the size of the downturn is lower. On impact for instance, for all model specifications considered, output decreases below the steady state about $1,5\%$ when $\rho_R = 0$, and about 1% when $\rho_R = 0,8$. As an implication of a milder recession, the fall in real marginal costs is less pronounced, or equally, the rise in mark-ups is less strong -the latter grows in all specifications at around 6% when $\rho_R = 0$, while at around 4% when $\rho_R = 0,8$-. Notwithstanding, inflation surges on impact driven by a weaker contraction in nominal marginal costs. Inflation also remains above the steady state level for some periods, although the response persistence is lower than in the case with no monetary policy smoothness. The positive dynamics is however common among all model specifications, independently from the presence of sticky real wages or consumption habits. The lower reactiveness of monetary policy does prevent nominal interest rate from initially increasing in response to the uncertainty shock, as the inflation does. Nominal interest rate starts to fall gradually and, at about one year later, lies below the long-run level.

To gain more insights on how much output and inflation dynamics are sensitive to the monetary policy stance, Figure 7 shows the responses of the two variables at four different monetary policy rules. The impulse response functions in the upper plots of Figure 7. are obtained by feeding a real uncertainty shock to the model described in Section 3.1., considering sticky real wages and no habits in consumption.[15] In each version of the model, the monetary policy rule (23) is calibrated differently. The first two rules have been already introduced, namely, i) a standard Taylor rule with $\rho_R = 0,8$, $\rho_\Pi = 1,5$, $\rho_Y = 0,125$, and ii) a Taylor rule with no smoothness with $\rho_R = 0$, $\rho_\Pi = 1,5$, $\rho_Y = 0,125$. The second two rules only target the inflation, namely iii) a weak inflation targeting rule with $\rho_R = 0$, $\rho_\Pi = 1,2$, $\rho_Y = 0$, and ii) a strong inflation targeting rule with $\rho_R = 0$, $\rho_\Pi = 5$, $\rho_Y = 0$. Inflation response is positive not only under a standard Taylor rule with persistence as argued above, but also under a weak inflation targeting rule. Under the latter however, after the initial boost, inflation decreases and falls below the steady state level before approaching it. The quick reversion of prices helps to make less heavy the contraction in output. Deviations in output and inflation are almost null, albeit slightly negative on impact, when the monetary authority pursues a strong inflation target. This suggests a first conclusion for the inflation behavior after a real uncertainty shock. Its dynamics is strictly related to the responsiveness of the monetary authority. The smoothness of the monetary policy determines the sign of the inflation response, while its aggressiveness toward inflation changes determines the magnitude of the inflation response.

[15] This model specification allows to be more parsimonious in terms of the inertia in the economy. Section 3.4.3 below, deals however with the different impact responses of inflation in model specifications with consumption habits.

3.4.2 Nominal uncertainty shocks

Figures 5-6.show the model dynamics after a second order shock to the nominal interest rate. Only the case of sticky prices is considered. The model specifications shown in Figures 5-6 are same of the previous Section 3.4.1. Figure 5. shows the impulse response functions under the case of no persistent monetary policy, i.e. $\rho_R = 0$, while Figure 6. under the case of persistent monetary policy, i.e. $\rho_R = 0,8$.

Case of sticky prices A first remark to do is on the size of the effects of nominal volatility shocks with and without monetary policy persistence. Differently from the case of real uncertainty shocks, the smoothness degree in monetary policy abruptly changes the magnitude of the effects. The aggregate variables responses in Figure 5., where ρ_R is fixed to 0, are about one order lower than the responses in Figure 6., where ρ_R is fixed to $0,8$. It means that putting to zero the autoregressive parameter of the Taylor rule, the effects of nominal uncertainty shocks are negligible in comparison with the alternative case.[16] This is extremely clear from Figure 7., which compares the responses of inflation and output to different monetary policy rules -namely the same rules described above in Section 3.4.2-. Conditional to the nominal volatility shock, the response of economic activity and inflation are really significant only by assuming a positive persistence in the monetary policy in line with empirical evidence.

By looking however at the shape of the responses in Figures 5 and 6., the dynamics triggered by a nominal volatility shock is contractionary in economic activity under both monetary policies. Inflation and nominal interest rate instead, do not respond uniformly. With no persistence in the monetary rule, the responses of inflation and nominal interest rate are mixed among the specifications considered. They are negative for the specifications with habits, while they are positive for the specifications without habits. Albeit this contrasts with the case of real uncertainty shock, the overall effects are quantitatively limited in both variables.[17] With persistence in the monetary rule, the responses of inflation and nominal interest rate are substantial and positive for all the specifications. This is furthermore consistent with the case of a real uncertainty shock. More in general, when the effects to the economy are quantitatively comparable, as in the specifications with inertia in monetary policy, the responses to real and nominal

[16] This is true, although the nominal interest rate is affected by nominal uncertainty shocks both on impact and onward, via the influence they have to inflation and output. This occurs if the equation governing the nominal interest rate, i.e. the Taylor rule, is assumed dependent upon inflation and output. Otherwise, since second order shocks enters the Taylor rule as a cross-product with uncorrelated first order shocks, they could not affect the level of nominal interest rate.

[17] The different dynamics of inflation is explained by the price mark-up behavior. The two specifications with no habits face a heavier recession. Price mark-ups, which are defined as the inverse of real marginal costs, rise then more. Inflation eventually reacts positively as a result of the growing mark-ups, which totally compensate the fall in nominal marginal costs.

uncertainty shocks are very similar among the variables. This supports the claim that how a growing uncertainty affects the agents behaviors and finally spreads out in the economy, is not actually dependent on which kind of shock has caused that higher uncertainty.[18]

3.4.3 Varying monetary policy smoothness

Figures 8-11.show the impact response of inflation to real and nominal uncertainty shocks to different model parametrization. Specifically, the figures show how the impact response of inflation changes as monetary policy smoothness parameter varies in conjuction with degrees of respectively i) consumption habits, ii) wage stickiness, ii) interest rate reaction to inflation, and iv) interest rate reaction to output.

The trajectories of the inflation responses at different ρ_R are positively-shaped for almost all calibrations considered in i)-iv). As monetary policy smoothness approaches to values supported by the empirical evidence, the impact response of inflation monotonically grows by changing sign from negative to positive. An exception is represented by the upper panel in Figure 10. For very low inflation reaction coefficients in the Taylor rule, the trajectories of inflation responses are no more positively-shaped. The impact is already positive for low levels of monetary policy persistence and decline as the latter increases, remaining above the zero line. Since however too low values for the inflation reaction parameter, bring the model nearer to the indeterminacy region, the results under these extreme calibrations need to be taken with cautions. A high variability in the inflation impact responses also holds by calibrating differently the internal habits on consumption. As the degree of habits raises, the impact response of inflation increases as well -becoming positive still for low levels of monetary policy persistence from about $h = 0,5$ on-.Importantly, the response trajectory remains positive-shaped as habits degree increases. The inertia in monetary policy then matters for the inflation outcome still with a smoother profile in consumption. The inflation responses vary less as degrees of real wage stickiness and output reaction coefficients in the Taylor rule change. In both cases, the inflation impact is negative when ρ_R is calibrated below $0,5 - 0,6$ and becomes positive onward.

For the nominal uncertainty shocks, the value of the coefficient ρ_R is still more crucial to assess the inflation response. As the inertia in monetary policy increases, the impact response of inflation changes from being small and near to zero to being high and positive. Specifically as the smoothness parameter is set above to $0,7$, the inflation response increases considerably in magnitude. Remarkably, its profile is consistent among the different calibration i)-iv). The dispersion of the responses trajectories increases only

[18] On regards, Born and Pfeifer (2014) simulate several policy-related and technology-related uncertainty shocks, and find a general common pattern of the macroeconomic variables in response to different uncertainty shocks.

by changing the calibration of the nominal interest rate reaction to inflation. The more aggressive is the central bank against inflation, the flatter becomes the inflation response at any given ρ_R. As expected, a central bank that weights more price growth deviations, is more able to keep inflation expectations close to the target. This still occurs after a shock increasing the uncertainty about the future monetary policy. By increasing ρ_Π, the response of inflation to a policy uncertainty shocks declines, but remains positive.

4. Conclusions

This paper studies the macroeconomic effects of uncertainty shocks under different specifications of monetary policy. Starting from the evidence that a higher uncertainty is depressing for the real activity, the paper focuses on the nominal side of the economy, and more in particular, on the inflation response to volatility shocks. Albeit most of the exiting literature agree that uncertainty shocks are not only contractionary but still deflationary, this paper shows in a DSGE environment, that inflation response is highly sensitive to the inertia of the monetary policy. By simulating indeed, an uncertainty shock to the realizations of the aggregate productivity, real variables face a recession independently from the persistence degree of the monetary policy. For the inflation conversely, the response changes the sign according to the reactiveness of the monetary policy. The sign is negative when the calibrated autoregressive coefficient of the monetary rule is very low levels near to zero, and becomes positive when the same coefficient is fixed at values widely accepted by the empirical evidence -around $0,7-0,9$-. Conditional to an uncertainty shock to the realizations of the nominal interest rate, the degree of the monetary rule persistence instead determines the overall magnitude of the effects of that shock. These effects are limited at low smoothness degree of monetary policy and significantly increase at smoothness degrees in line with the data. In particular for the latter, the volatility shock to the nominal interest rate triggers a strong contraction in output and a hike in prices.

The DSGE model simulations stress then the relevance of the monetary policy to interpret the consequences of a second order shock that increase uncertainty in the economy. An issue that has been partially neglected by the related literature so far. This paper shows that the cost to pay to replicate the contemporaneous bust in output and inflation found with a linear VAR might be high. To accommodate the VAR evidence in a general equilibrium model, the monetary policy needs a calibration that is far from the reality. This opens new challenges for the ongoing research on the macroeconomic effects of uncertainty. More investigations are needed both on the theoretical and empirical side. In light of the different inflation outcome in the theoretical model, an optimal monetary policy analysis comes naturally as a future step. On the empirical side instead, the estimation of a non-linear VAR model could provide deeper insights on the effects of shocks of order higher than one. A feasible strategy is to integrate the empirical model in order to evaluate the inflation response to uncertainty innovations in relation to the different inertia in monetary policy. Both exercises are left for the future research.

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A. Appendix

A.1 System of equations

1) Marginal utility of consumption

$$\lambda_t = \frac{1}{C_t - hC_{t-1}} - \beta E_t \frac{h}{C_{t+1} - hC_t} \ ,$$

2) Euler equation

$$\frac{1}{R_t} = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\Pi_{t+1}} \right] \ ,$$

3) Nash bargaining real wage

$$w_t^{NB} = \omega \left(\alpha \Lambda_t \frac{Y_{I,t}}{N_t} + (1-s)\, \beta E_t \frac{\lambda_{t+1}}{\lambda_t} \frac{p_{t+1}}{q_{t+1}} \frac{\kappa}{\lambda_{t+1}} \right) + (1-\omega) \left(\frac{\chi N_t^{\eta}}{\lambda_t} + b \right) \ ,$$

4) Actual real wage

$$w_t = (w_{t-1})^{\gamma} \left(w_t^{NB} \right)^{1-\gamma} \ ,$$

5) Production function

$$Y_t = Z_t N_t^{\alpha} \left(a_t K_{t-1} \right)^{1-\alpha} \ ,$$

6) Resource constraint

$$\left(1 - \Gamma\left(\Pi_t\right)\right) Y_t = C_t + \left(1 + \Upsilon \left(\frac{I_t}{I_{t-1}} \right) \right) I_t \ ,$$

7) Phillips curve

$$\Lambda_t = \frac{\varepsilon_p - 1}{\varepsilon_p} + \frac{\phi^P}{\varepsilon_p} (\Pi_t - \Pi) \Pi_t - \frac{\beta}{\varepsilon_p} E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{Y_{t+1}}{Y_t} \phi^P (\Pi_{t+1} - \Pi) \Pi_{t+1} \right] ,$$

8) Return of capital

$$Q_t = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} (a_{t+1} MPK_{t+1} + Q_{t+1} (1 - \delta(a_{t+1}))) \right] ,$$

9) Marginal productivity of effective capital

$$MPK_t = (1 - \alpha) \Lambda_t \frac{Y_{I,t}}{a_t K_{t-1}} ,$$

10) Investment equation

$$Q_t = 1 + \Upsilon \left(\frac{I_t}{I_{t-1}} \right) + \Upsilon' \left(\frac{I_t}{I_{t-1}} \right) \frac{I_t}{I_{t-1}} - \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \right) \Upsilon' \left(\frac{I_{t+1}}{I_t} \right) \left(\frac{I_{t+1}}{I_t} \right)^2 ,$$

10) Rental rate of capital

$$Q_t \delta_t'(a_t) = MPK_t ,$$

11) Capital law of motion

$$\gamma \tilde{K}_t = \tilde{I}_t + (1 - \delta(a_t)) \tilde{K}_{t-1}$$

12) Job firm surplus

$$J_t^F = \alpha \Lambda_t \frac{Y_{I,t}}{N_t} - w_t + (1 - s) \beta E_t \left(\frac{\lambda_{t+1}}{\lambda_t} \right) J_{t+1}^F ,$$

13) Job creation condition

$$J_t^F = \frac{\kappa}{\lambda_t q_t} ,$$

14) Matching function

$$m_t = \mu u_t^{\varphi} v_t^{1-\varphi} ,$$

15) Vacancy filling probability

$$q_t = \frac{m_t}{v_t} ,$$

16) Job finding probability

$$p_t = \frac{m_t}{u_t} ,$$

17) Employment law of motion

$$N_t = (1 - s)\, N_{t-1} + m_t \ ,$$

18) Job searcher workers

$$u_t = 1 - (1 - s) N_{t-1} \ ,$$

19) Unemployment rate

$$U_t = 1 - N_t \ ,$$

20) Total factor productivity

$$\log\left(\frac{Z_t}{Z}\right) = \rho_Z \log\left(\frac{Z_{t-1}}{Z}\right) + \sigma_{Z,t}\varepsilon_t^Z \ ,$$

21) Stochastic volatility of productivity

$$\log\left(\frac{\sigma_{Z,t}}{\sigma_Z}\right) = \rho_{\sigma_Z} \log\left(\frac{\sigma_{Z,t-1}}{\sigma_Z}\right) + \sigma_{\sigma_Z}\varepsilon_t^{\sigma^Z} \ ,$$

22) Taylor rule

$$\log\left(\frac{R_t}{R}\right) = \rho_R \log\left(\frac{R_{t-1}}{R}\right) + (1 - \rho_R)\left(\rho_\Pi\left(\frac{\Pi_t}{\Pi}\right) + \rho_Y\left(\frac{Y_t}{Y}\right)\right) + \sigma_{R,t}\varepsilon_t^R \ ,$$

23) Stochastic volatility of nominal interest rate

$$\log\left(\frac{\sigma_{R,t}}{\sigma_R}\right) = \rho_{\sigma_R} \log\left(\frac{\sigma_{R,t-1}}{\sigma_R}\right) + \sigma_{\sigma_R}\varepsilon_t^{\sigma^R} \ .$$

Table 1. Model Calibration

$\beta =$	$0,992$	preference discount factor
$\theta =$	1	intertemporal elasticity of substitution
$\eta =$	1	inverse of Frisch elasticity
$h =$	0	benchmark habits persistence
$\alpha =$	$0,66$	labor share
$\phi^I =$	$2,48$	investment adjustmtment cost parameter
$\delta =$	$0,025$	steady state depreciation rate
$\delta_2 =$	$0,1\delta_1$	II depreciation rate parameter
$U =$	$0,1$	steady state unemployment rate
$q =$	$0,7$	vacancy filling probability
$\varphi =$	$0,5$	elasticity parameter in matching function
$\omega =$	$0,5$	worker bargaining power
$\gamma =$	$0,8$	real wage indexation degree
$\kappa =$	$0,02\left(\frac{Y}{v}\right)$	vacancy posting costs
$b =$	$0,25$	unemployment benefit
$\varepsilon_P =$	10	elasticity of substitution among varieties
$\phi^P =$	110	price adjustmtment cost parameter
$\Pi =$	$1,005$	steady state gross inflation rate
$Z =$	1	steady state TFP level
$\rho_Z =$	$0,9$	persistence degree of TFP level
$\rho_R =$	$0,8$	benchmark Taylor rule smoothness parameter
$\rho_\Pi =$	$1,5$	benchmark Taylor rule inflation weight parameter
$\rho_Y =$	$0,125$	benchmark Taylor rule output-gap weight parameter
$\sigma_Z =$	$0,01$	steady state st.dev of TFP level
$\sigma_R =$	$0,01$	steady state st.dev of nominal interest rate
$\rho_{\sigma_Z} =$	$0,6817$	persistence of TFP volatility shock
$\rho_{\sigma_R} =$	$0,3759$	persistence of nominal interest rate volatility shock
$\sigma_{\sigma_Z} =$	$0,1759$	st.dev of TFP volatility shock
$\sigma_{\sigma_R} =$	$0,4752$	st.dev of nominal interest rate volatility shock

Figures

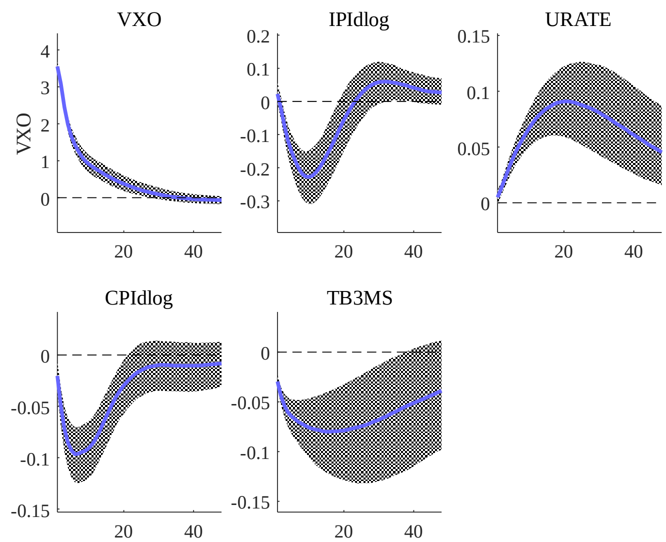

Figure 1. IRFs of a one standard deviation shock to VXO index. The blue solid line represents the median impulse response function. The shaded area the credible interval (16-84 percentiles interval).

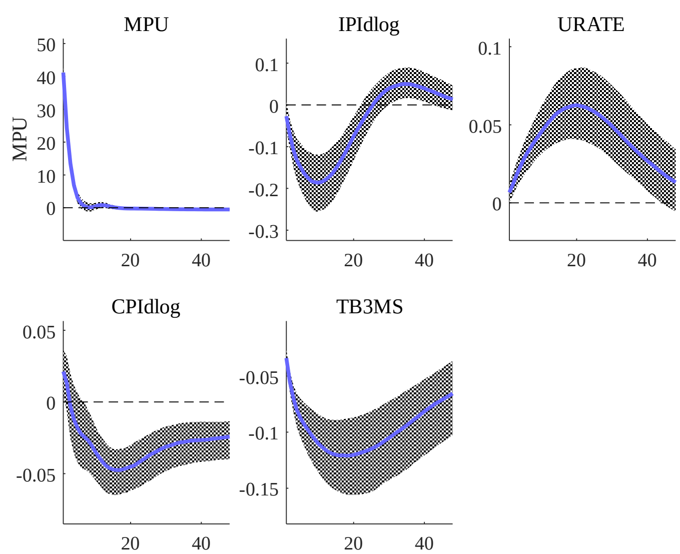

Figure 2. IRFs of a one standard deviation shock to MPU index. The blue solid line represents the median impulse response function. The shaded area the credible interval (16-84 percentiles interval).

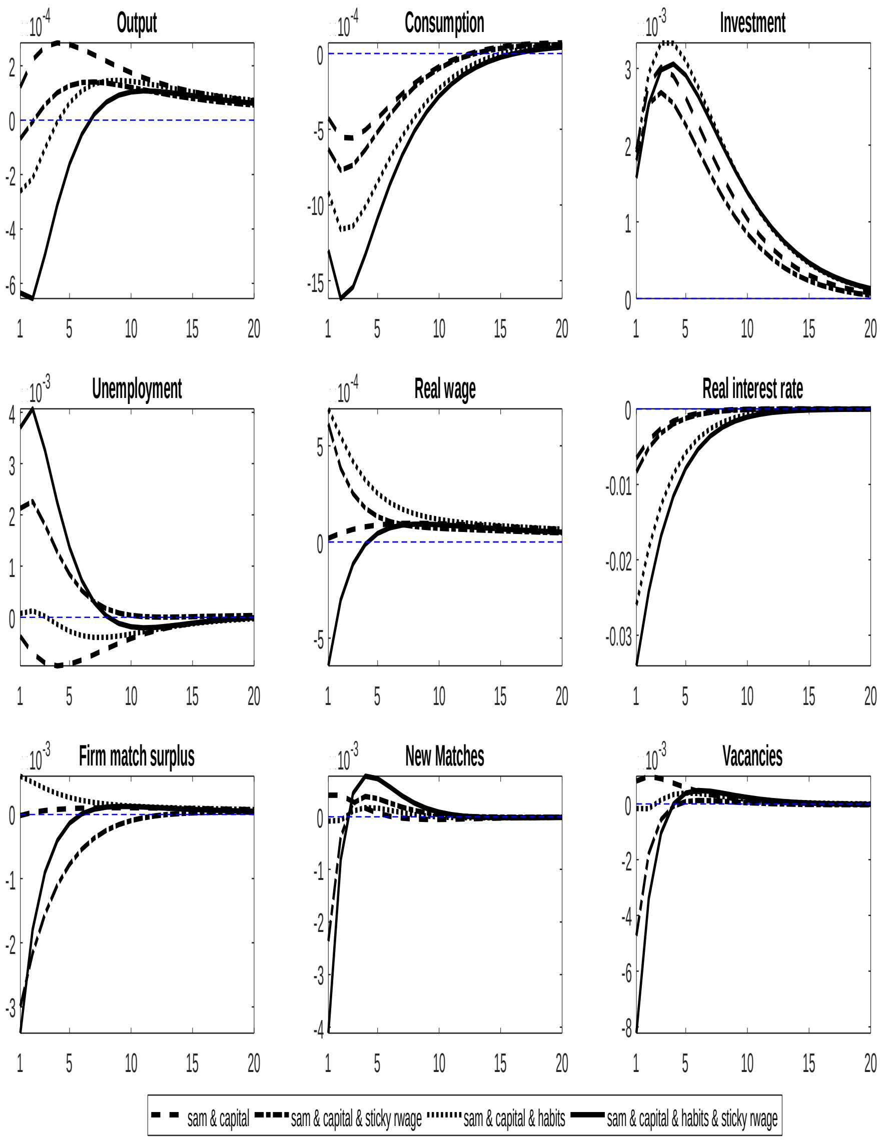

Figure 2. IRFs to a *real* uncertainty shock in model specification with flexible prices. Dashed line: RBC model without consumption habits, sticky real wages, but with capital, search and matching frictions (sam). Dashed-dotted line: RBC model without consumption habits, but with capital, sam frictions, sticky real wages. Dotted line: RBC model without real sticky wages, but with capital, sam frictions, consumption habits. Solid line: RBC model with capital, sam frictions, consumption habits, sticky real wages.

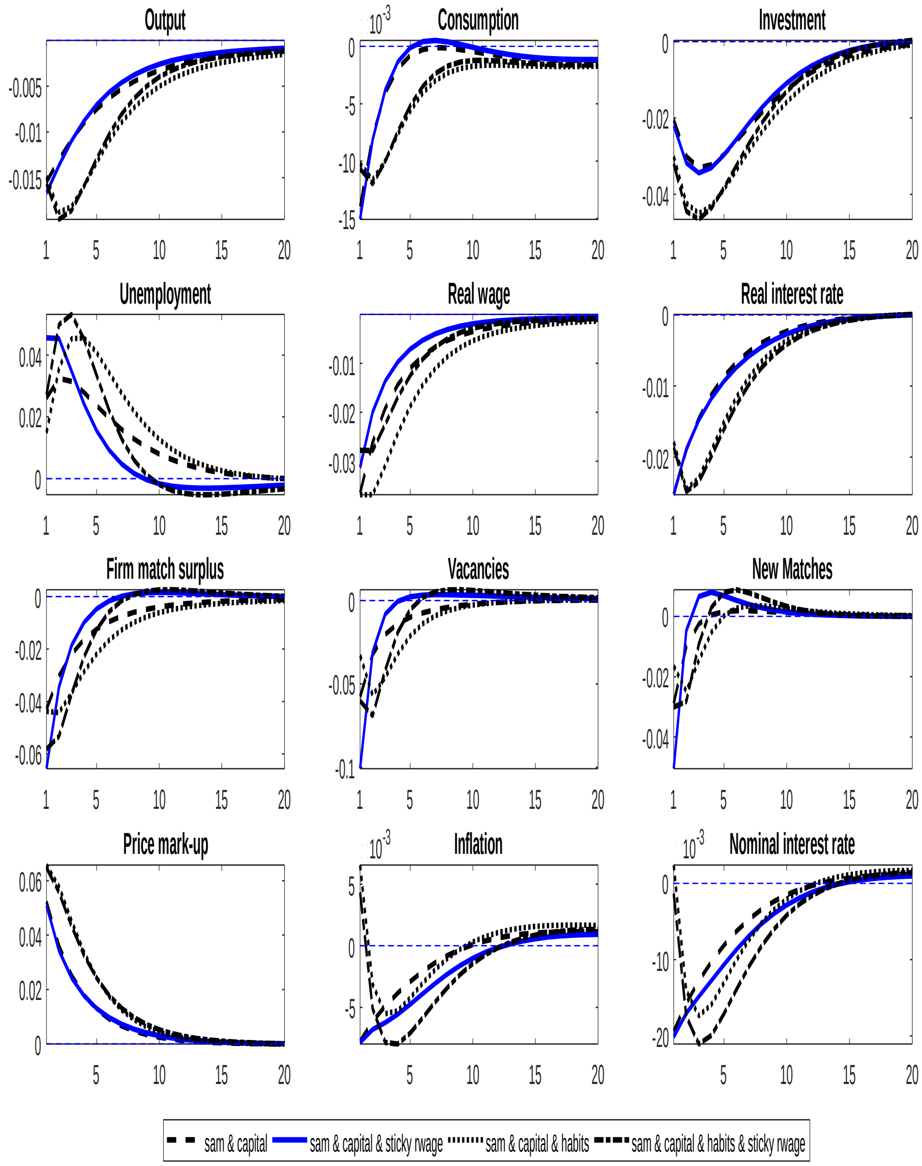

Figure 3. IRFs to a *real* uncertainty shock in model specification with sticky prices and $\rho_R = 0$. Dashed line: NK model without consumption habits, sticky real wages, but with capital, search and matching frictions (sam). Solid blu line: NK model without consumption habits, but with capital, sam frictions, sticky real wages. Dotted line: NK model without real sticky wages, but with capital, sam frictions, consumption habits. Dashed-dotted line: NK model with capital, sam frictions, consumption habits, sticky real wages.

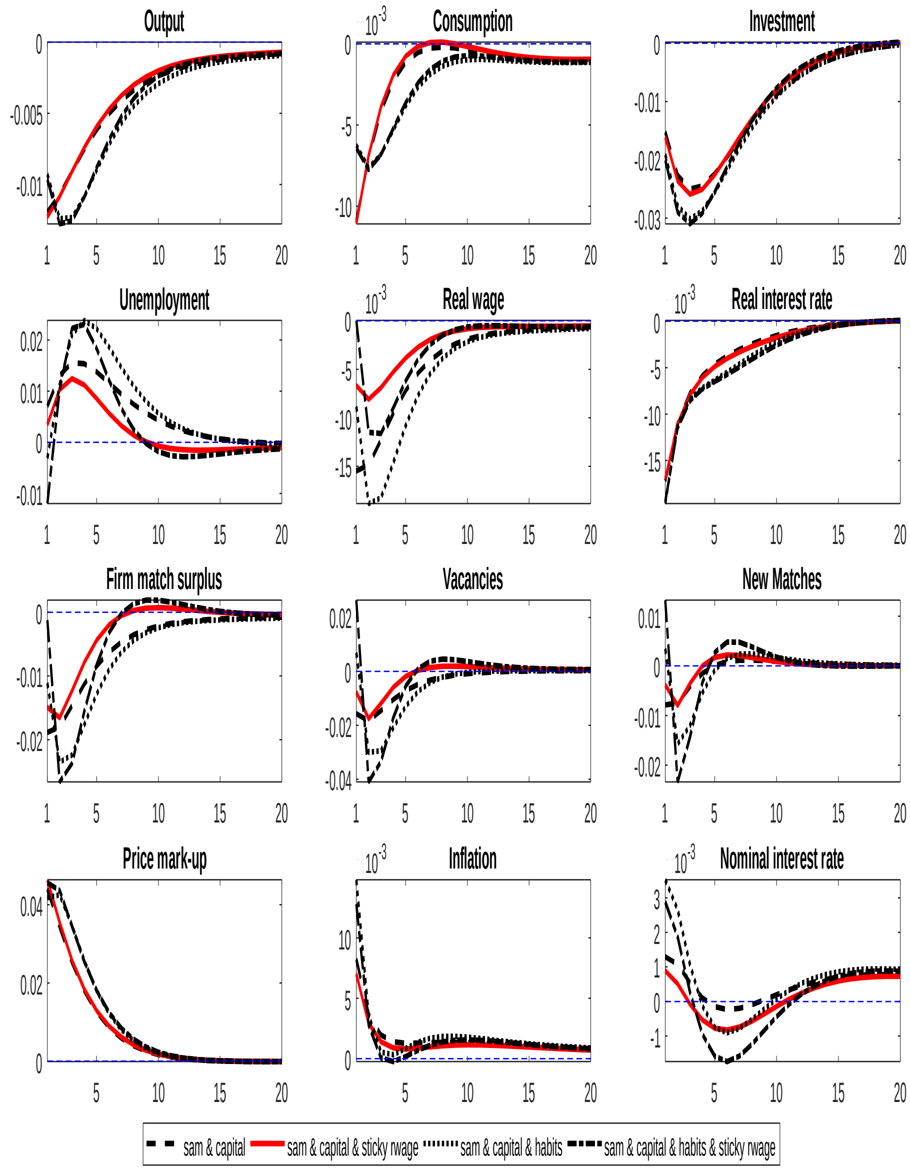

Figure 4. IRFs to a *real* uncertainty shock in model specification with sticky prices and $\rho_R = 0,8$. Dashed line: NK model without consumption habits, sticky real wages, but with capital, search and matching frictions (sam). Solid red line: NK model without consumption habits, but with capital, sam frictions, sticky real wages. Dotted line: NK model without real sticky wages, but with capital, sam frictions, consumption habits. Dashed-dotted line: NK model with capital, sam frictions, consumption habits, sticky real wages.

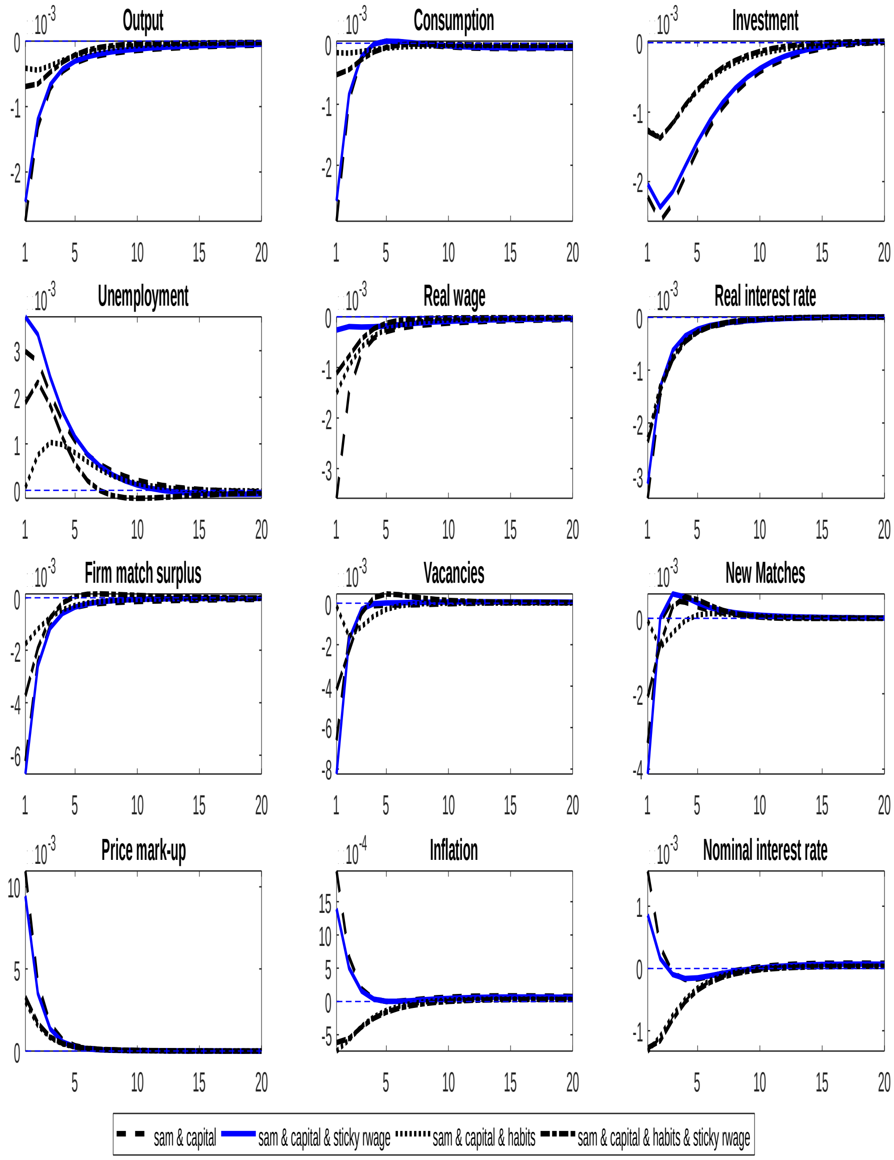

Figure 5. IRFs to a *nominal* uncertainty shock in model specification with sticky prices and $\rho_R = 0$. Dashed line: NK model without consumption habits, sticky real wages, but with capital, search and matching frictions (sam). Solid blu line: NK model without consumption habits, but with capital, sam frictions, sticky real wages. Dotted line: NK model without real sticky wages, but with capital, sam frictions, consumption habits. Dashed-dotted line: NK model with capital, sam frictions, consumption habits, sticky real wages.

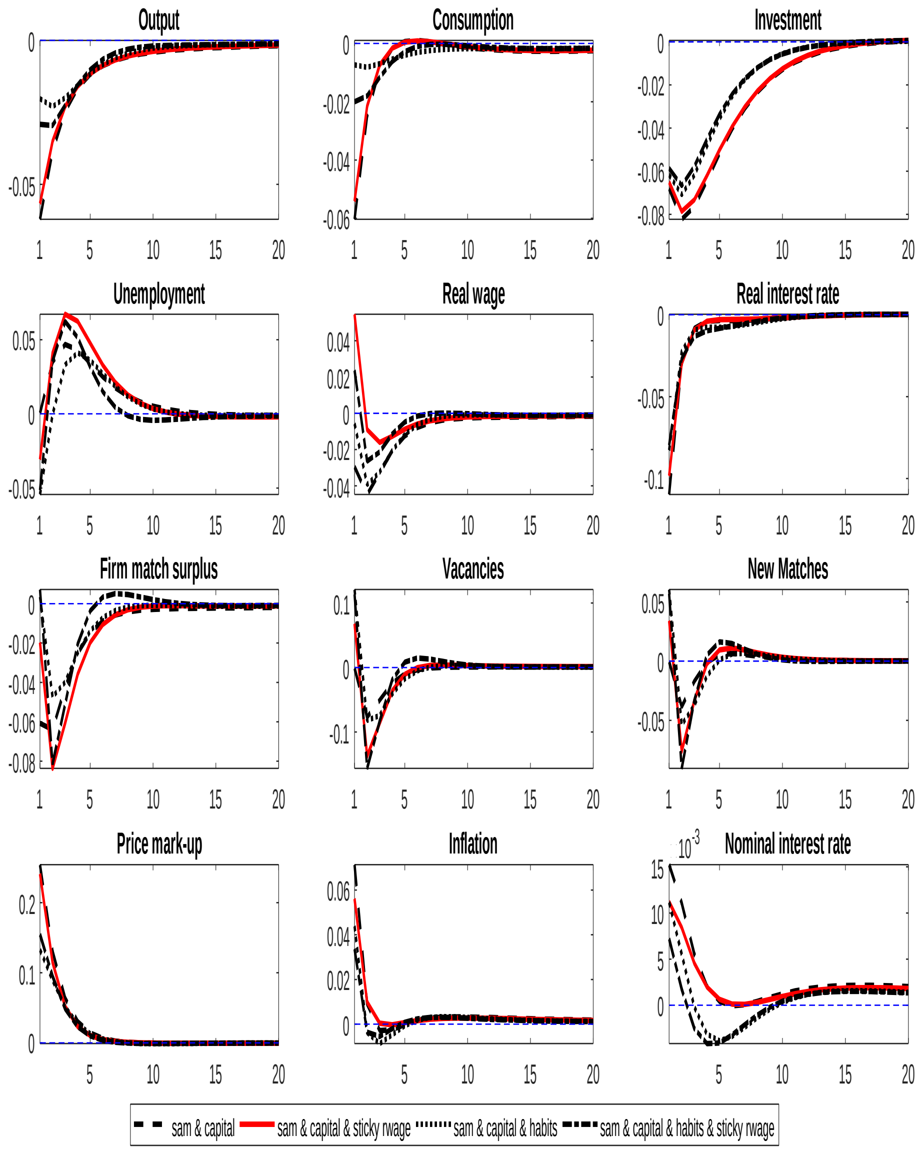

Figure 6. IRFs to a *nominal* uncertainty shock in model specification with sticky prices and $\rho_R = 0,8$. Dashed line: NK model without consumption habits, sticky real wages, but with capital, search and matching frictions (sam). Solid red line: NK model without consumption habits, but with capital, sam frictions, sticky real wages. Dotted line: NK model without real sticky wages, but with capital, sam frictions, consumption habits. Dashed-dotted line: NK model with capital, sam frictions, consumption habits, sticky real wages.

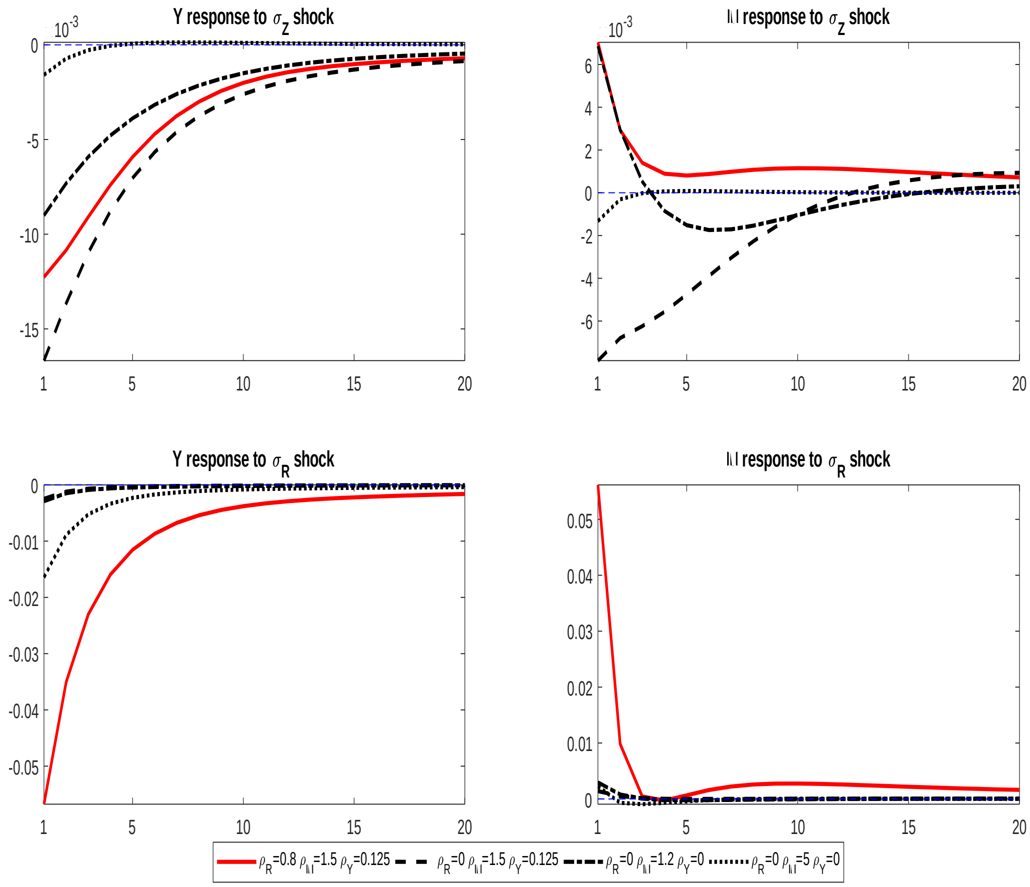

Figure 7. IRFs of output (left column) and inflation (right column) to *real* uncertainty shock (upper plot) and to *nominal* uncertainty shock (below plot) at different Taylor rule specifications. Solid red line: $\rho_R = 0,8$, $\rho_\Pi = 1,5$, $\rho_Y = 0,125$. Dashed line: $\rho_R = 0$, $\rho_\Pi = 1,5$, $\rho_Y = 0,125$. Dashed-dotted line: $\rho_R = 0$, $\rho_\Pi = 1,2$, $\rho_Y = 0$. Solid red line: $\rho_R = 0,0$, $\rho_\Pi = 5$, $\rho_Y = 0$.

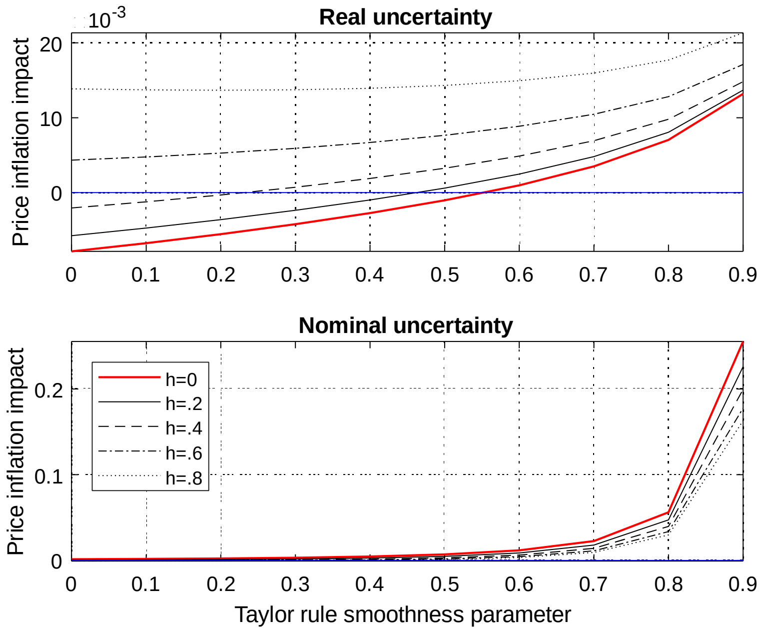

Figure 8. Impact responses of inflation to *real* uncertainty shock (upper plot) and to *nominal* uncertainty shock (below plot) at different Taylor rule smoothness parameters and at different degrees of consumption habits.

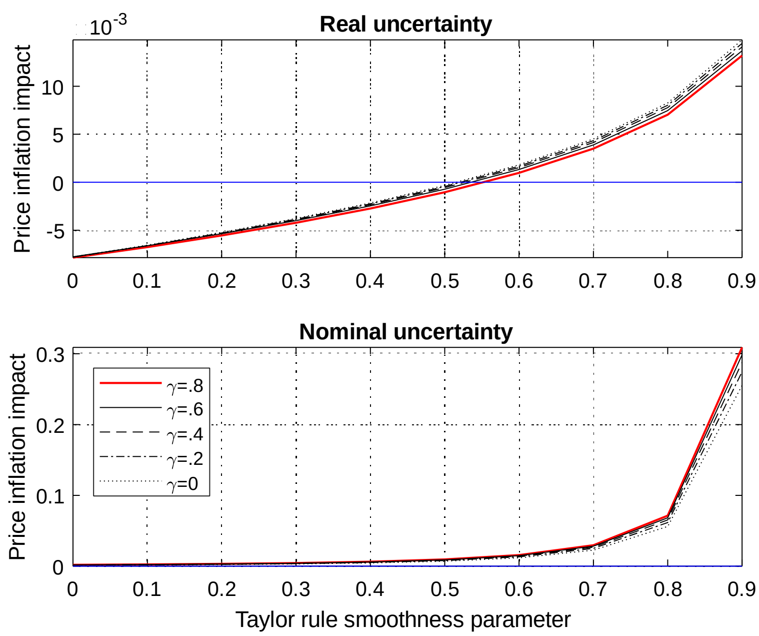

Figure 9. Impact responses of inflation to *real* uncertainty shock (upper plot) and to *nominal* uncertainty shock (below plot) at different Taylor rule smoothness parameters and at different degrees of stickiness in real wages.

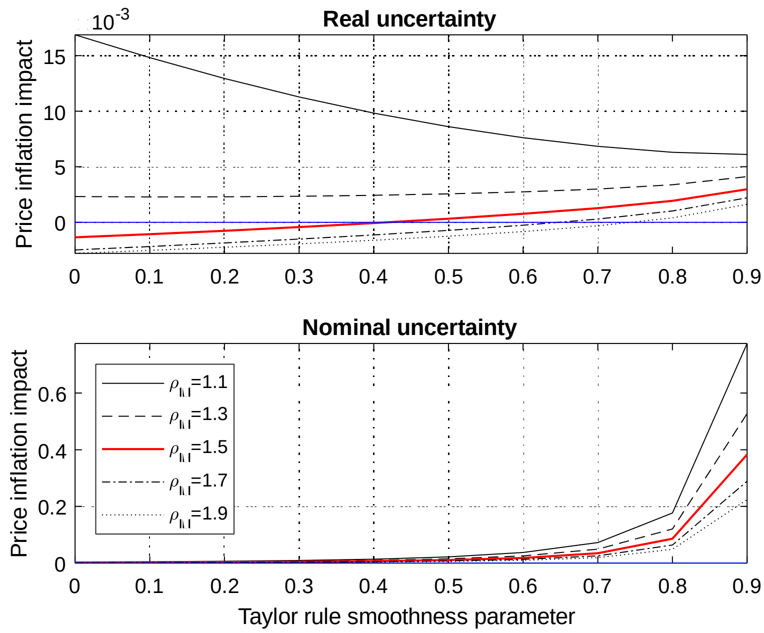

Figure 10. Impact responses of inflation to *real* uncertainty shock (upper plot) and to *nominal* uncertainty shock (below plot) at different Taylor rule smoothness parameters and at different Taylor rule inflation weight.

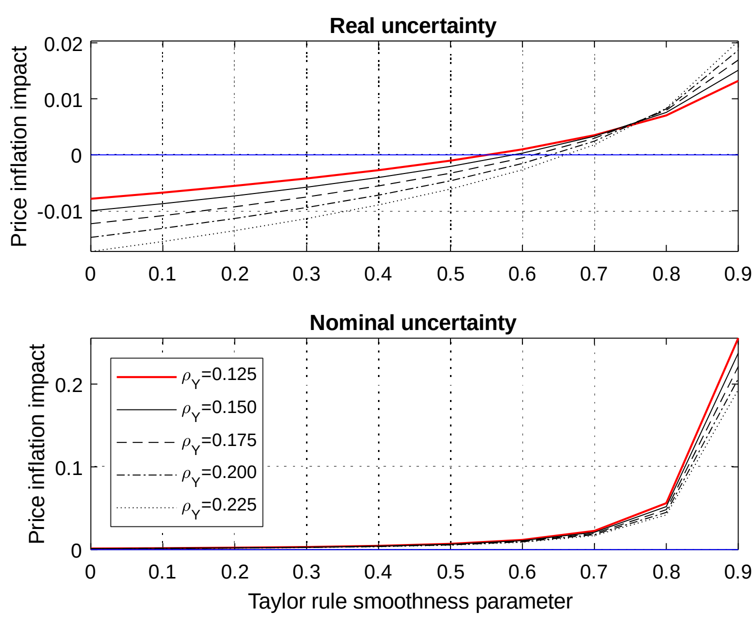

Figure 11. Impact responses of inflation to *real* uncertainty shock (upper plot) and to *nominal* uncertainty shock (below plot) at different Taylor rule smoothness parameters and at different Taylor rule output-gap weight.

Figure 12. IRFs to a *real* uncertainty shock in model specification with flexible prices. Solid line: RBC model without capital, search and matching frictions (sam), consumption habits. Dotted line: RBC model without capital, sam frictions, but with consumption habits. Dashed line: RBC model without sam frictions, consumption habits, but capital. Dashed-dotted line: RBC model without capital, consumption habits, but sam frictions.

Figure 13. IRFs to a *real* uncertainty shock in model specification with sticky prices and $\rho_R = 0$. Solid blu line: NK model without capital, search and matching frictions (sam), consumption habits. Dotted line: NK model without capital, sam frictions, but with consumption habits. Dashed line: NK model without sam frictions, consumption habits, but capital. Dashed-dotted line: NK model without capital, consumption habits, but sam frictions.

Figure 14. IRFs to a *real* uncertainty shock in model specification with sticky prices and $\rho_R = 0,8$. Solid red line: NK model without capital, search and matching frictions (sam), consumption habits. Dotted line: NK model without capital, sam frictions, but with consumption habits. Dashed line: NK model without sam frictions, consumption habits, but capital. Dashed-dotted line: NK model without capital, consumption habits, but sam frictions.

Figure 15. IRFs to a *nominal* uncertainty shock in model specification with sticky prices and $\rho_R = 0$. Solid blu line: NK model without capital, search and matching frictions (sam), consumption habits. Dotted line: NK model without capital, sam frictions, but with consumption habits. Dashed line: NK model without sam frictions, consumption habits, but capital. Dashed-dotted line: NK model without capital, consumption habits, but sam frictions.

Figure 16. IRFs to a *nominal* uncertainty shock in model specification with sticky prices and $\rho_R = 0$. Solid blu line: NK model without capital, search and matching frictions (sam), consumption habits. Dotted line: NK model without capital, sam frictions, but with consumption habits. Dashed line: NK model without sam frictions, consumption habits, but capital. Dashed-dotted line: NK model without capital, consumption habits, but sam frictions.