Unexpected Effects: Uncertainty, Unemployment, and Inflation*

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Abstract

This paper studies the impact of uncertainty on economic activity in a canonical search-and-matching framework with risk-averse households. A mean-preserving spread to *future* productivity contracts *current* output even in the absence of nominal rigidities, although the effect is significantly reinforced by the presence of the latter. This result reveals that uncertainty shocks carry both contractionary demand and supply effects. In particular, a more uncertain future increases the precautionary behavior of households, which reduces interest rates and contracts demand. At the same time, as future asset prices are more volatile and positively covary with aggregate consumption, households demand a larger risk premium, which puts negative pressure on current asset values and contracts supply. Thus, in comparison to a pure negative demand shock, an uncertainty shock puts less deflationary pressure on the economy and, as a result, renders a flatter Phillips curve. In contrast to a common explanation in the literature, these results do not rely on any option-value considerations.

Keywords: Uncertainty, risk, unemployment, inflation, search frictions, Phillips curve.
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1 Introduction

This paper studies the impact of uncertainty on labor market dynamics and inflation in a canonical search-and-matching framework with risk-averse households. The associated question – how do uncertainty shocks contribute to macroeconomic fluctuations? – has received considerable attention from policymakers and economists alike over the past few years.[1] Much of the academic work on uncertainty in macroeconomics has concentrated on the behavior of firms in capital and product markets. In this paper, we instead consider the implications of stochastic volatility for labor market dynamics. In doing so, we draw on and highlight additional implications of work in the field of macro-labor, where researchers have fruitfully shown how incorporating labor market frictions into quantitative macroeconomic models can aid in accounting for key business cycle properties of macroeconomic aggregates.[2]

We use a theoretical framework that combines four key ingredients: (i.) a Mortensen and Pissarides (1994) type labor market with matching frictions, random search, and wage bargaining; (ii.) risk-averse households; (iii.) price-setting by monopolistically competitive firms that may be subject to rigidities; and (iv.) stochastic volatility in shocks to aggregate labor productivity. The model is described in detail in Section 2. We deliberately consider a canonical environment that features just enough richness to evaluate the joint dynamics of real and nominal labor market variables, notably unemployment and inflation. Our objective is not to introduce additional modeling complexity but, rather, to shed light on perhaps unexpected effects of uncertainty in an oft-used framework. By imposing restrictions on the encompassing model we can identify the different channels through which uncertainty shocks affect economic activity in this canonical setting and explain the intuition underlying these mechanisms. For purposes of numerical analysis, we solve the model non-linearly and construct a subset of generalized impulse response functions that capture the "pure uncertainty effects" associated with agents adjusting their behavior in response to a mean-preserving spread to the distribution of future aggregate labor productivity shocks. Intuitively, we focus on the effect uncertainty has on expectations, and specifically how expectations of greater future volatility in productivity trickle through to actual decisions, but abstract from realized shocks to the level of productivity.

The key insight from our analysis is that the impact of uncertainty shocks on economic activity is distinctively characterized by the simultaneous operation of both contractionary supply and demand

[1] For instance, referring to such events as "economics tensions between China and the US, geopolitical developments in the Middle East (with the associated risk of a sharp rise in oil prices), and the political deadlock over Brexit," Boone and Buti of the OECD and European Commission write that "high and increasingly entrenched uncertainty is sufficient to put a brake on investment and growth," even if these risks do not materialize but remain "looming threats" (Boone and Buti, 2019).

[2] Three prominent examples of many are Gertler *et al.* (2008), Blanchard and Galí (2010) and Christiano *et al.* (2016).

transmission mechanisms. Search frictions in the labor market play an important role in giving rise to these supply effects as well as creating a novel source for demand effects. In contrast to a common explanation in the literature, these results do *not* rely on any option-value considerations. They *do* imply, on the other hand, that an economy subject to uncertainty shocks renders a flatter Phillips curve than the same economy buffeted by "traditional" demand shocks.

More specifically, the paper advances four main claims. We enumerate them first for sake of clarity before elaborating on each of the points and placing them in the context of the literature.

(i) First, there is no option-value channel in the canonical search-and-matching model through which uncertainty shocks lead to rising unemployment, but rather a "Nash-wage channel" (Section 3.1).

(ii) Second, a mean-preserving spread to future productivity contracts current output even in the absence of nominal rigidities due to a risk premium effect (Section 3.2).

(iii) Third, when nominal rigidities are operative, the contraction in current and expected future demand following an increase in uncertainty amplifies the recession (Section 3.3).

(iv) Finally, an uncertainty shock puts less disinflationary pressure on the economy than a pure negative aggregate demand shock (Section 4.1).

Our first argument stands in contrast to the influential hypothesis articulated in Leduc and Liu (2016) that integrating labor market search frictions into an otherwise standard business cycle model gives rise to real options effects. This hypothesis suggests that due to the irreversibility of employment relationships in the model, an increase in uncertainty raises the option value of waiting and thus induces firms to hold back on creating new jobs.[3] The intuitive reason why the model cannot feature option-value consideration of this sort is that the free-entry condition that is at the core of the framework eliminates any option value embedded in vacancies.[4] We establish an analytical irrelevance result to the effect that uncertainty shocks have no macroeconomic consequences in a linear utility version of the model with no nominal rigidities and wages that are linear in productivity. Numerical exercises corroborate this view.

Uncertainty shocks *can* have real effects in the search-and-matching framework even under the assumptions of flexible prices and risk-neutrality when wages are non-linear in productivity, that

[3] Fasani and Rossi's (2018) comment on Leduc and Liu's (2016) likewise discusses their findings through the lens of real options theory. Similar observations apply to Guglielminetti (2016).

[4] Schaal (2017) presents a labor market model featuring directed search in which real options effects *do* exist, although they appear to be small in magnitude. In Schaal's model, firms operate a decreasing returns to scale technology and the free-entry condition obtains at the firm level rather than the vacancy level. As a result, the value of posting a vacancy does vary over time. This implies that firms face an optimal timing problem when deciding on the number of vacancies to create in a given period, giving rise to real options effects.

is, when we introduce additional non-linearities into the model on top of those arising from the presence of search frictions. The operative mechanism is unrelated to option-value considerations, however.[5] Specifically, under the popular assumption of Nash bargaining, wages are positively affected by (expected) labor market conditions over and above the direct impact of productivity shocks. The "Nash-wage channel" then arises from the interaction of that wage specification and the fact that labor market tightness is convex in productivity given a concave matching function. These two considerations imply that the marginal profit from creating a new establishment by hiring another worker is concave in productivity. Hence, an uncertainty shock leads a firm to anticipate that the future marginal establishment profitability will be lower on average, thus depressing hiring activity and putting upward pressure on unemployment. In the remaining analysis we adopt a linear wage specification inspired by the alternating offer bargaining mechanism analyzed in Hall and Milgrom (2008) in order to examine the implications of search frictions without the confounding influence of the Nash-wage channel.

Our second set of results shows that the interaction of risk-aversion and search frictions means that an uncertainty shock affects supply side dynamics in the economy such that an uncertainty shock causes current output to fall even when prices are flexible. In particular, when future volatility in the economy is expected to rise, the conditional covariance between future firm dividends and aggregate consumption becomes more positive. Accordingly, risk-averse households require greater compensation for holding (now riskier) equity compared to safe government-issued bonds. In the search-and-matching framework, this amounts to households demanding a greater risk premium to hold firms' equity. The implied increase in the cost of equity funding leads to a fall in job-creation. Thus, this risk premium channel has an unambiguously negative effect on employment.

At the same time, a more uncertain future also increases the precautionary behavior of households, which reduces interest rates and contracts demand. To appreciate the mechanism, envisage that a mean-preserving volatility shock causes risk-averse households to expect future volatility to be elevated. Now, several contributions to the search-and-matching literature (e.g., Hairault *et al.* (2010); Jung and Kuester (2011); Petrosky-Nadeau *et al.* (2018)) have shown that search frictions give rise to non-linear dynamics such that business cycle volatility raises average unemployment. Intuitively, employment losses during recessions outweigh the gains during booms. Other things equal, therefore, when agents expect the level of future volatility to be elevated, they also expect to have less disposable income available for consumption (we find it helpful to think of this logic as a kind of "endogenous pessimism"). The corresponding increase in expected future marginal utility *raises* households' desired savings today; equivalently, the yields on bonds that are used to discount future dividends paid out by job-creating establishments fall. As households' valua-

[5] Leduc and Liu (2016) furthermore argue that real options effects are reinforced when prices are sticky. We offer a discussion of the interaction between search frictions and nominal rigidities below.

tion of firm equity accordingly increases, firms respond by posting more vacancies, boosting job finding rates and ultimately lowering unemployment. We coin this expansionary mechanism the "asymmetry-discounting" effect. It merits emphasis that this channel is premised upon risk-aversion rather than prudence in the utility function (in the Kimball (1990) sense of marginal utility being convex). As such, the logic we describe operates even under linear marginal utility and reflects a mechanism distinct from and operating on top of prudence.[6] Under flexible prices, the impact of an uncertainty shock reflects the operation of both the (contractionary) risk premium channel and precautionary savings behavior due to asymmetric employment dynamics and potentially prudence. Under log utility, numerical analysis reveals the former to be dominating the latter, suggesting that the integration of labor market search frictions can, in principle, help explain the negative impact of uncertainty on economic activity.

Third, sticky prices gives rise to an additional demand channel that exacerbates the recession observed under flexible prices, as precautionary savings behavior by households – due to both prudence in preferences and "endogenous pessimism" associated with the asymmetries inherent in frictional labor markets – now carries negative effects. Notably, elevated uncertainty engenders expectations for depressed future aggregate demand, as before. Under sticky prices this triggers a fall in the expected price attached to the goods produced using labor, exerting a negative effect on job-creation and employment in the present. Our numerical analysis shows that the recession caused by an uncertainty shock is potentially much deeper than is the case without nominal rigidities. We also emphasize a potential tradeoff facing the monetary authority when prices are sticky due to Rotemberg price adjustment costs. In our benchmark scenario, where price adjustment costs do not enter the economy's resource constraint, the central bank is able to effectively stabilize the economy by reacting with sufficient strength to output gaps. If, however, these adjustment costs do affect the amount of production left over for consumption, then monetary authorities face an uncomfortable tradeoff between fluctuations in employment and inflation, either of which triggers negative demand effects.

Our analysis of transmission channels through which uncertainty shocks affect economic activity ties into literature too vast to comprehensively discuss here (for surveys, see Bloom (2014) and Castelnuovo (2019)).[7] Contributions to that literature have highlighted the potential of stochastic volatility to affect economic dynamics through a whole variety of channels.[8] The environment

[6]Both the asymmetry-discounting effect and prudence in the utility function give rise to a form of precautionary savings. However, while the prudence effect arises mechanically from a positive third derivative of the utility function, the asymmetry-discounting channel rests on the interaction of a negative second derivative and the non-linear endogenous propagation of shocks in the economy.

[7]A by no means exhaustive list of references in addition to the ones mentioned below includes: Andreasen (2012); Bachmann and Bayer (2013); Christiano *et al.* (2014); Mongey and Williams (2017); Ghironi and Ozhan (2019); Bonciani and Oh (2019); Sedláček (2019); Berger *et al.* (2019).

[8]A somewhat schematic list includes: real options effects arising in the presence of non-convex adjustment costs (e.g.,

considered here embeds some of the listed effects, while emphasizing their distinctive operation within the context of frictional labor markets, explicitly excludes others, notably real options effects, and reveals new transmission mechanisms that arise distinctively in the presence of search frictions. In this regard, and as noted above, our paper is closest to Leduc and Liu (2016), whose model we borrow although our view on the transmission mechanisms at play is different.[9] Our hope is that through both substantial insights and the methodological "tricks" used to pin down the operation of specific transmission mechanisms this paper contributes to a better understanding of the complex and non-linear ways in which uncertainty shocks affect economic activity.

Finally, for our fourth claim we combine qualitative and quantitative analysis to argue that, *pace* Leduc and Liu (2016), uncertainty shocks are not equivalent to aggregate demand shocks. Instead, they combine features of demand- and supply disturbances in a distinctive way. From a conceptual vantage point, the principal reason why uncertainty shocks are different from aggregate demand shocks is the presence of the risk premium channel, which has inflationary consequences. Numerically, simulations show that for any given contractionary impact on unemployment, a conventional aggregate demand shock has a more negative impact on inflation than an uncertainty shock. Correspondingly, because uncertainty shocks combine features of demand shocks with supply features, an economy hit by uncertainty shocks will display a Phillips Curve relationship that appears flatter than the same economy subject to demand shocks. These differences are more marked the greater the household's degree of risk-aversion. Our perspective on uncertainty shocks as being distinct from aggregate demand shocks may help rationalize the empirically contested response of inflation to uncertainty shocks, which led Castelnuovo (2019) to conclude that more work is needed to understand the response of inflation to uncertainty shocks.[10] Moreover, the relatively more disinflationary impact of uncertainty shocks compared to demand shock raises the intriguing possibility that elevated uncertainty levels in the Financial Crisis and Great Recession may help resolve the "missing disinflation" puzzle, according to which inflation in rich economies

Bloom (2009) and Bloom *et al.* (2018)); risk premium effects (e.g., Fernández-Villaverde *et al.* (2011); Cesa-Bianchi and Fernandez-Corugedo (2018)); precautionary savings (e.g., Bansal and Yaron (2004)) as well as precautionary labor supply by households and their interaction with sticky prices (e.g., Basu and Bundick (2017)); Oi-Hartman-Abel effects (e.g., Oi (1961); Hartman (1972); Abel (1983)); and precautionary pricing by product-price and wage setters (e.g.,Fernández-Villaverde *et al.* (2015); Born and Pfeifer (2019); Bachmann *et al.* (2019), also coined "reverse Oi-Hartman-Abel effects" by Born and Pfeifer (2014a)).

[9] Cacciatore and Ravenna (2018) likewise consider the propagation of first- and second moment shocks to productivity in a model with search frictions, but focus on the implications of downward wage rigidity, whereas we primarily consider the case of symmetric, flexible wages and instead focus on the role of risk-aversion, nominal rigidities, and their interaction of search frictions.

[10] Fernández-Villaverde *et al.* (2015), Leduc and Liu (2016), Basu and Bundick (2017), Oh (2019) find that, empirically, the inflation rate tends to fall after uncertainty shocks; though no explicit comparison is drawn to "pure" demand shocks. On the other hand, Meinen and Roehe (2018) identify uncertainty shocks using sign restrictions and find the reaction of prices to be ambiguous. Alessandri and Mumtaz (2019) employ a regime-switching VAR framework and find uncertainty shocks to be inflationary in normal times, although deflationary during financial crisis.

in 2008-2009 failed to decline as much as expected given the steep rise in unemployment (cf. Hall (2011)). In the concluding Section 5 we provide further discussion of this conjecture but leave the empirical evaluation to future work.

2 Theoretical Framework

The economy is populated by a unit measure of households; a competitive sector of intermediate goods firms producing a homogenous input good; a monopolistically competitive sector of final good producers; and a central bank which sets the policy interest rate. Real quantities are defined in terms of the final good, and are – unless otherwise stated – denoted by lower case letters. Time is discrete and denoted $t = 0, 1, 2, \ldots$

2.1 Households

In a given period t, a household can either be employed, n_t, or unemployed, u_t. The market for idiosyncratic employment risk is complete, however, so the representative household – or simply *the household* – is comprised by a measure of n_t members that are working, and u_t members that are not. Non-employed members of the household may find a job even within the period they get displaced. Thus, the measure of the household's members that are searching for a job in the beginning of a period is $u_t^s = u_{t-1} + \delta n_{t-1}$, where δ denotes an exogenous separation rate. The measure of employed individuals working in period t is therefore given by $n_t = f_t u_t^s + (1-\delta)n_{t-1}$, where f_t denotes an endogenously determined job finding rate. The real wage is denoted w_t and, as there is no home production, total labor income is given by $w_t n_t$.

In addition to labor income, the household enters the period with nominal bonds, B_{t-1}, and equity a_{t-1}. Equity is valued at the cum-dividend price J_t. However, as a fraction, δ, of firms goes out of business in each period, the total value of the household's equity position is $J_t a_{t-1}(1-\delta)$. The household also receives profits from several other sources: the aforementioned monopolistically competitive final goods firms, vacancy-creating firms, and (possibly) price adjusting firms. However, since these entities cannot affect, nor be affected by, the household's decisions, we summarize their total profits in the variable $\tilde{d}_t$, which is, for the moment, treated as given (see section 2.5 for a more detailed description).

The household may use the resources available in period t – i.e. labor income, bond and equity holdings, and the additional profits – to either consume the final good, c_t; purchase new equity, a_t, at the ex-dividend price $J_t - d_t$; or purchase nominal bonds, B_t, at the price $1/(P_t R_t)$, where P_t denotes the aggregate price level, and R_t the gross nominal interest rate.

Thus, the budget constraint of the household is

$$c_t + a_t(J_t - d_t) + \frac{B_t}{P_t R_t} = w_t n_t + \tilde{d}_t + \frac{B_{t-1}}{P_t} + a_{t-1}(1-\delta)J_t, \quad t = 0,1,2,\dots, \tag{1}$$

where a_{-1} and B_{-1} are given.

Subject to the above budget constraint, the household decides on a process, $\{c_t, a_t, B_t\}_{t=0}^{\infty}$, to maximize the expected present discounted value of lifetime household utility

$$E_0 \sum_{t=0}^{\infty} \beta^t u(c_t), \tag{2}$$

where E_0 denotes the mathematical expectation operator; the parameter $\beta \in (0,1)$ represents the subjective discount factor, and the period utility function, $u(\cdot)$, satisfies $u'(\cdot) > 0$ and $u''(\cdot) < 0$.

The first order conditions associated with the household's problem is given by a bond Euler equation

$$u'(c_t) = \beta E_t \left[\frac{R_t}{\Pi_t} u'(c_{t+1}) \right], \tag{3}$$

as well as an Euler equation for equity

$$u'(c_t) = \beta E_t \left[\frac{J_{t+1}(1-\delta)}{J_t - d_t} u'(c_{t+1}) \right]. \tag{4}$$

Rearranging the latter and defining $\Lambda_{t,t+1} = \beta u'(c_{t+1})/u'(c_t)$ gives the asset pricing equation

$$J_t = d_t + E_t \left[\Lambda_{t,t+1} J_{t+1} (1-\delta) \right]. \tag{5}$$

The asset pricing equation for equity will play an integral part of the equilibrium outcome as intermediate goods producing firms will generate dividends $d_t = x_t z_t - w_t$, where z_t denotes the marginal product of a worker, and x_t the relative price of intermediate goods. Thus, if intermediate goods producers generate a dividend process of $\{d_t\}_{t=0}^{\infty}$, their asset price, or firm value, is determined by equation (5), which in turn will determine firm entry. This relationship will be discussed in detail in the next section.

Lastly, we define the risk free real interest rate as

$$R_t^{rf} = \frac{1}{E_t[\Lambda_{t,t+1}]}, \tag{6}$$

and the risk premium on equity as

$$RP_t = \frac{E_t[J_{t+1}](1-\delta)}{J_t - d_t} - R_t^{rf}. \tag{7}$$

2.2 Firms

2.2.1 Intermediate goods producers

There is a large number of potential intermediate goods producing firms, but a finite measure of operating (or active) firms. The firms use labor as the only input to production in a constant returns to scale technology, producing a homogenous good. Thus, without any loss of generality we will assume that each active firm employs precisely one worker. As a consequence, the measure of active intermediate firms equals the employment rate, n_t.

An active firm produces z_t units of intermediate goods, where z_t represents a workers marginal product. These goods are sold to final goods firms at price x_t, and the firms pay workers the wage w_t. Hence, each intermediate good firms generate (real) profits of $x_t z_t - w_t$. As a consequence, the value of an intermediate good producing firm is given by

$$J_t = x_t z_t - w_t + E_t\left[\Lambda_{t,t+1} J_{t+1}(1-\delta)\right]. \tag{8}$$

Potential intermediate goods firms may enter the market by posting a vacancy. The (marginal) cost of posting a vacancy is denoted κ, which result in the firm meeting a searching household with probability h_t. Thus, the free-entry condition is given by

$$\kappa = h_t J_t. \tag{9}$$

We assume that the aggregate resources devoted to vacancy posting – i.e. κv_t, where v_t denotes the aggregate amount of vacancies posted in period t – is rebated back to the households. That is, the households are assumed to own the vacancy posting agency.

Lastly, there are exogenous stochastic processes for labor productivity, z_t, and the standard deviation of labor productivity, $\sigma_{z,t}$. Both are modeled as the AR(1) processes

$$z_t = (1-\rho_z)z + \rho_z z_{t-1} + \sigma_{z,t-1}\varepsilon_{z,t}, \tag{10}$$

$$\sigma_{z,t} = (1-\rho_\sigma)\sigma_z + \rho_\sigma \sigma_{z,t-1} + \varepsilon_{\sigma_z,t}. \tag{11}$$

Importantly, the standard deviation of the innovation to productivity, $\varepsilon_{z,t}$, is time-varying. The parameters $\rho_z \in (-1,1)$ and $\rho_\sigma \in (-1,1)$ measure the persistence of the first- and second-moment shocks, respectively. Additionally, σ_z is the steady-state value of the standard deviation of the innovation to productivity. Both shocks $\varepsilon_{z,t}$ and $\varepsilon_{\sigma_z,t}$ are normally distributed with $\sigma_{\varepsilon_z} = 1$, and where $\sigma_{\varepsilon_\sigma}$ will be calibrated.[11]

2.2.2 Final and retail goods producers

Final goods firms are perfectly competitive and use retail goods as the only input. However, as retail goods operates under monopolistic competition, they take into account the demand schedule that materializes from final goods optimal production decision. As a consequence, we discuss both these firms under the same section, starting with the final goods producers.

Final goods producers. The final consumption good, y_t, is produced using a constant elasticity of substitution (CES) production function according to

$$y_t = \left(\int_0^1 y_t(i)^{\frac{\eta-1}{\eta}} di \right)^{\frac{\eta}{\eta-1}},$$

where $y_t(i)$ denotes the retail good produced by firm i, with $i \in [0,1]$. The parameter η denotes the elasticity of substitution between the differentiated retail goods.

Let $p_t(i)$ denote the relative price associated with retail good i. The optimization problem facing the final goods producers is then given by

$$\max_{y_t(i)_{i\in[0,1]}} \left\{ P_t y_t - \int_0^1 p_t(i) y_t(i) \right\},$$

where P_t denotes the aggregate price level/index.

The first order conditions to this optimization problem give rise to the demand schedule

$$y_t(i) = \left(\frac{p_t(i)}{P_t} \right)^{-\eta} y_t, \tag{12}$$

with the associated price index

$$P_t = \left(\int_0^1 P_t(i)^{\frac{1}{1-\eta}} di \right)^{1-\eta}.$$

Retail goods producers. Differentiated retail goods are produced using the homogeneous intermediate good as the single input. The technology is such that one unit of the intermediate good produces one unit of the retail good. As the relative price of the intermediate good *in terms of the*

[11]Notice that under the timing assumption in equation (10), which is common in the uncertainty shock literature (e.g., Bloom (2009); Schaal (2017)), volatility shocks have a delayed impact on the distribution of labor productivity shocks.

final good is given by x_t, retailers make per-period profits[12]

$$\frac{p_t(i)}{P_t} y_t(i) - x_t y_t(i). \tag{13}$$

However, as we at times will consider a situation in which retailers can not adjust prices frictionlessly, but only may do so by incurring a cost, a more general formulation for the retailers profits is given by

$$\hat{d}_t = \frac{p_t(i)}{P_t} y_t(i) - x_t y_t(i) - \frac{\Omega_p}{2}\left(\frac{p_t(i)}{p_{t-1}(i)\Pi} - 1\right)^2 y_t, \tag{14}$$

where Π denotes the steady stead gross inflation rate, P_t/P_{t-1}. Thus, the period profits $\hat{d}_t$, nest equation (13) in the special case of $\Omega_p = 0$.

Using the pricing relation in equation (5), but denoting the asset price of retailers as $v_t(p_t(i))$ yields

$$v_t(p_t(i)) = \hat{d}_t + E_t\left[\Lambda_{t,t+1} v_{t+1}(p_{t+1}(i))\right]. \tag{15}$$

Taking into account the demand schedule in equation (12), as well as the definition of the per-period profits in equation (14), the first order condition associated with optimizing the firm value above is given by the non-linear new Keynesian Phillips curve

$$x_t = \frac{\eta - 1}{\eta} + \frac{\Omega_p}{\eta}\left\{\frac{\Pi_t}{\Pi}\left(\frac{\Pi_t}{\Pi} - 1\right) - E_t\left[\Lambda_{t,t+1}\frac{y_{t+1}}{y_t}\frac{\Pi_{t+1}}{\Pi}\left(\frac{\Pi_{t+1}}{\Pi} - 1\right)\right]\right\}, \tag{16}$$

in which we have assumed symmetry, such that $p_t(i) = P_t$.

We again assume that the aggregate resources devoted to price changes, that is

$$\frac{\Omega_p}{2}\left(\frac{\Pi_t}{\Pi} - 1\right)^2 y_t,$$

are rebated back to the households. That is, the households are assumed to own the price adjusting agency.

2.3 Labor markets

As already discussed in Section 2.1 the measure of unemployed workers searching for a job in period t is given by $u_t^s = u_{t-1} + \delta n_{t-1}$. And as discussed in Section 2.2.1 there is a measure v_t of

[12]Notice that we can equivalently think of x_t as the real marginal cost facing the retailer.

aggregate vacancies posted by intermediate goods firms. Matches in the labor market, M_t, are then determined according to a standard Cobb-Douglas function,

$$M_t = \psi(u_t^s)^\alpha (v_t)^{1-\alpha}, \tag{17}$$

where $\alpha \in (0,1)$ denotes the elasticity of matches with respect to job seekers u_t^s and ψ scales the matching efficiency. The implied hiring rate, h_t, is therefore

$$h_t = \frac{M_t}{v_t} = h(\theta_t) = \psi\theta_t^{-\alpha}, \tag{18}$$

where θ indicates labor market tightness which is given by

$$\theta_t = \frac{v_t}{u_t^s} = \frac{v_t}{1-(1-\delta)\, n_{t-1}}. \tag{19}$$

Analogously, the job finding probability for a searching worker is given by

$$f_t = \frac{M_t}{u_t^s} = f(\theta_t) = \psi\theta_t^{1-\alpha}. \tag{20}$$

Notice that $h(\theta)$ is strictly decreasing in θ while $f(\theta)$ is strictly increasing.

As discussed in Section 2.1, the law of motion for employment is given by

$$n_t = f_t u_t^s + (1-\delta)n_{t-1}, \tag{21}$$

$$= h_t v_t + (1-\delta)n_{t-1}, \tag{22}$$

$$= M_t + (1-\delta)n_{t-1}. \tag{23}$$

Together with the law of motion for employment, the equilibrium aggregate measure of vacancies posted in any given period, v_t, is endogenously determined as the solution to the free entry condition in equation (9), which is here repeated to explicitly account for the relationship between the asset price, J_t, and labor market tightness, θ_t,

$$\kappa = h(\theta_t)J_t. \tag{24}$$

2.3.1 Wage setting

Search frictions in the labor market imply that a matched firm and worker generate a joint surplus, and give rise to a situation of bilateral monopoly. This latter aspect leaves wages, without any further theory, undetermined. To this end, the benchmark analysis will consider a wage-setting protocol determined by *alternating offers*. This contrast to the more common practice of wage-setting through *Nash bargaining*.[13] The primary reason favoring the former rather than the latter is that traditionally Nash-bargained wages carries a forward looking component that has some particularly undesirable effects when analyzing uncertainty shocks. This latter point will be more thoroughly elaborated on in section 3.1.

Alternating offers Wage setting based on alternating offers stems from the observation that severing a match is not a credible threat; indeed the worker and the firm will always reach an agreement within the period the match occurs. Common knowledge of this feature implies that future variables bear no consequence on the currently agreed wage.

The alternating-offers game takes place in fictional time, in which each time-period is of length Δ. If the worker has the opportunity of proposing a wage, w_t, she will offer the highest possible value that the firm will accept. That is, the wage will yield the worker a maximum value of $\overline{v}_w = w_t$, and the firm a minimum value of $\underline{v}_f = x_t z_t - w_t$. However, as the firm can reject the wage proposal and wait to the next (fictional) time-period to make a counteroffer, the minimum value must also satisfy $\underline{v}_f = e^{-\Delta\omega} \times \overline{v}_f$, where $\overline{v}_f$ denotes the firm's maximum value, and $e^{-\Delta\omega}$ the discount factor.

Conversely, if the firm has the opportunity of proposing a wage, w'_t, it will yield the firm a maximum value of $\overline{v}_f = x_t z_t - w'_t$, and the worker a minimum value of $\underline{v}_w = w'$. Again, as the worker can reject the wage proposal and wait to the next (fictional) time-period to make a counteroffer, the worker's minimum value must also satisfy $\underline{v}_w = \Delta\hat{\chi} + e^{-\Delta(1-\omega)} \times \overline{v}_w$, where $\Delta\hat{\chi}$ represents the flow utility the worker receives by not working. Notice that the worker and the firm discounts fictional time differently; a higher value of ω renders workers more patient which will play to the worker's advantage, and vice versa.

The above set-up provides six (linear) equations in six unknowns. Solving this system and letting Δ approach zero gives rise to a unique (subgame perfect) wage that is agreed upon immediately

$$w_t = \omega x_t z_t + (1-\omega)\chi, \tag{25}$$

with $\chi = \hat{\chi}/(1-\omega)$. That is, the agreed wage is a combination of the firm's revenues and the flow utility the worker receives by delaying agreement.[14]

[13] See Binmore *et al.* (1986) for a discussion of the relationship between these alternative arrangements; Hall and Milgrom (2008) provide an in-depth exploration of the implications in a search-and-matching model similar to the one considered here.

[14] This wage coincides exactly with that of Jung and Kuester (2011), which sets wages by maximizing the Nash product $(w_t - \chi)^{\omega}(x_t z_t - w_t)^{1-\omega}$.

Nash bargained wages To provide a comparison of the predictions of the model using alternating offers wages with those using Nash bargaining, we define a value of a match for a worker, V_t, as

$$V_t = w_t + E_t\left[\Lambda_{t,t+1}\left((1-\delta)V_{t+1} + \delta U_{t+1}\right)\right],$$

and the value of unemployment, U_t, as

$$U_t = \zeta + E_t\left[\Lambda_{t,t+1}\left(f_{t+1}V_{t+1} + (1-f_{t+1})U_{t+1}\right)\right],$$

where ζ denotes some utility of leisure or home production. Thus, the surplus of a match, S_t is given by

$$S_t = w_t - \zeta + E_t\left[\Lambda_{t,t+1}\left(1-\delta-f_{t+1}\right)S_{t+1}\right].$$

Nash bargained wages are then set according to

$$w_t^N = \text{argmax}\{S_t^{\omega} J_t^{1-\omega}\},$$

or using some algebraic manipulations

$$w_t^N = \omega x_t z_t + (1-\omega)\zeta + \omega\kappa E_t[\Lambda_{t,t+1}\theta_{t+1}]. \tag{26}$$

Comparing the wages in equations (25) and (26) reveals that *if* ζ is such that

$$\zeta = \chi - \frac{\omega}{1-\omega}\kappa E[\Lambda\theta],$$

the two wages coincide in the stochastic steady state. However, as will be apparent in section 3.1, the two specifications can give rise to profoundly different dynamics in response to uncertainty shocks. While these issues are too intricate to be discussed at this state, it suffices to note that holding x_t constant (i.e. under flexible prices), adopting the alternating offers formulation in equation (25) allows us to focus on the non-linearities that are intrinsic to the matching process, without confounding the results from those arising from any non-linearities that are specific to the wage bargain, nor imposing that wages are completely rigid.[15]

[15] Hall and Milgrom (2008) proposes a bargaining specification that partially insulates wages from variations in labor market tightness. Equation (25) is a special case insofar as this isolation is complete. Additionally, it leaves the wage unresponsive to movements in the marginal utility of consumption.

2.4 Monetary policy

The central bank sets the nominal interest rate, R_t, according to the Taylor rule

$$\log\left(\frac{R_t}{R}\right) = \phi_\pi \log\left(\frac{\Pi_t}{\Pi}\right) + \phi_y \log\left(\frac{y_t}{y}\right). \tag{27}$$

In the presence of nominal rigidities, monetary policy can stimulate employment and production by cutting the interest rate, R_t. A lower interest rate increases demand for the final good through the bond Euler equation in (3). Increased demand for final goods leads retail firms to set higher prices and to increase demand for intermediate goods, putting upward pressure on the relative price of intermediate goods, x_t. To the extent that the increase in marginal revenues, $x_t z_t$, is not entirely offset by an increase in wages, w_t, the intermediate firms posts additional vacancies until the free-entry condition (24). That is, until the probability of filling a vacancy, $h(\theta_t)$, has decreased sufficiently to ensure free entry.

In the case of flexible prices the above chain is broken. In particular, retail firms then adjust prices sufficiently to render the *real interest rate* unaffeced (as inflation expectations change), which entirely offsets the initial increase in demand. Indeed, under flexible prices, i.e. when $\Omega_p = 0$, it is trivial to see from equation (16) that the relative intermediate goods price, x_t, is constant at $x = (\eta - 1)/\eta$, which implies that there is also no additional entry. Nominal rigidities are therefore necessary to prevent these price movements to operate freely.

2.5 Market clearing and equilibrium

As all firms use a constant returns to scale technology – alongside with the fact that intermediate goods use only labor as an input good, retail firms use only intermediate goods, and final goods firms use only retail goods – aggregate output is given by $y_t = z_t n_t$.

As mention in section 2.1, the household makes additional profits, $\tilde{d}_t$. These profits are in excess of the dividends arising from the ownership of intermediate firms, and instead include per-period profits from retailers, vacancy posting firms, and price adjusting firms. Aggregate profits arising from vacancy posting firms is equal to κv_t. Moreover, the aggregate profit arising from retailers *net of price adjustment costs* is

$$\frac{p_t(i)}{P_t} y_t(i) - x_t y_t(i).$$

Using the fact that in a symmetric equilibrium $p_t(i) = p_t(j) = P_t$, alongside with the demand relation in equation (12) together with $y_t = z_t n_t$, reveals that these profits amount to $z_t n_t (1 - x_t)$.

Thus,

$$\tilde{d}_t = \kappa v_t + z_t n_t (1 - x_t). \tag{28}$$

Definition 1. *A competitive equilibrium is a process of prices* $\{J_t, R_t, \Pi_t, x_t, w_t\}_{t=0}^{\infty}$ *and quantities* $\{c_t, B_t, \theta_t, n_t, a_t\}_{t=0}^{\infty}$ *such that,*

(i) $\{c_t, B_t, a_t\}_{t=0}^{\infty}$ *solves the household's problem.*

(ii) *Asset prices* $\{J_t\}_{t=0}^{\infty}$ *satisfy the asset pricing equation in* (5).

(iii) *Labor market tightness,* $\{\theta_t\}_{t=0}^{\infty}$*, satisfies the free-entry condtion* $\kappa = h(\theta_t)J_t$.

(iv) *Employment,* $\{n_t\}_{t=0}^{\infty}$*, satisifies the law of motion*

$$n_t = [(1 - n_{t-1}) + \delta n_{t-1}] f(\theta_t) + (1 - \delta) n_{t-1}.$$

(v) *Wages,* $\{w_t\}_{t=0}^{\infty}$*, satisfy equation* (25).

(vi) *The gross nominal interest rate,* $\{R_t\}_{t=0}^{\infty}$*, satisfies the Taylor rule in equation* (27).

(vii) *Relative prices for intermediate goods and inflation,* $\{x_t, \Pi_t\}_{t=0}^{\infty}$*, satisfy the Phillips curve in equation* (16).

(viii) *Bond markets clear,* $B_t = 0$.

(ix) *Equity market clear,* $a_t = n_t$.

(x) *Intermediate goods markets clear* $y_t(i) = z_t n_t$.

Using the equilibrium relations $B_t = 0$ and $n_t = a_t$, the household's budget constraint is

$$c_t + n_t(J_t - d_t) = w_t n_t + \tilde{d}_t + n_{t-1}(1 - \delta) J_t.$$

Rearranging and using that fact that $d_t = x_t z_t - w_t$ gives

$$c_t + J_t(n_t - n_{t-1}(1 - \delta)) - = n_t x_t z_t + \tilde{d}_t.$$

Using the law of motion for employment in equation (22), and the definition of $\tilde{d}_t$ above reveals that

$$c_t + \kappa v_t - = n_t x_t z_t + \kappa v_t + z_t n_t (1 - x_t),$$

or simply $y_t = c_t = z_t n_t$.

Notice that aggregate consumptions is therefore not affected by the amount of vacancies created, nor the costs associated with price adjustments. This is indeed intentional; as we are exploring the role of uncertainty on behavior, any resource draining activity, such as price adjustments, will, somewhat mechanically, alter the marginal utility of consumption. Nevertheless, we will as a robustness exercise explore the role of such activities in sections 4.2 and A.4.

2.6 Numerical implementation

Below we outline the benchmark parameterization of the model and briefly discuss the key elements of the solution method, and how the main results are illustrated. Appendix A.5 provides additional details.

2.6.1 Parameterization

The parameterization largely follows that of Leduc and Liu (2016) and is outlined below. One period in the model is equivalent to one quarter. The period utility function is given by

$$u(c) = \frac{c^{1-\gamma} - 1}{1-\gamma},$$

where $u(c) = \ln(c)$ if $\gamma = 1$, and the matching function is given by

$$M_t = \psi(u_t^s)^{1-\alpha} v_t^{\alpha}.$$

In the benchmark specification the coefficient of relative risk aversion γ, is set to one. This is a conservative choice as the low value of risk aversion tends to downplay the role of uncertainty, and we explore the effects of larger values for the purpose of completeness. The discount factor β is set to 0.99 which implies a real interest rate of 4 percent in the steady state. Following Petrongolo and Pissarides (2001) the elasticity of the matching function, α, is set to 0.5, and so is the bargaining weight ω (cf. Hosios (1990)). We set the elasticity of substitution between differentiated retail product, η, to 10 which matches a steady state markup of 11 percent (Basu and Fernald, 1997). The matching efficiency parameter, ψ, is set to target an unemployment rate 6.4%.

According to the Job Openings and Labor Turnover Survey (JOLTS) the average monthly job separation rate is about 3.5 percent, which suggests a quarterly separation rate, δ, of about 0.1. To calibrate κ, we use the law of motion for employment in equation (22) and find that the measure of vacancies in the steady state is 0.134. Following Leduc and Liu (2016) we normalize the steady state value of labor productivity, z, to one, and then set κ such that the total cost of vacancy-posting is equal to 2 percent of steady state output.

The parameter governing price-stickiness, Ω_p, is set to 112 which, again following Leduc and Liu (2016), gives rise to a slope of the Phillips curve which is equal to that of an implied model with Calvo pricing – solved using a first order approximation – with a price resetting duration of four quarters. The parameters of the Taylor rule, ϕ_π and ϕ_y, are set to 1.5 and 0, respectively. Here we deviate from Leduc and Liu (2016) who set $\phi_y = 0.2$, as this choice tend to interact with the choice of the price adjustment parameter, Ω_p, and carry quite sizeable – although somewhat mechanical – quantitative implications. We will elaborate more on this in section 4.2.

The persistence and volatility of the productivity shock, ρ_z and σ_z, are set to the empirically relevant values of 0.9 and 0.01 respectively, which imply a standard deviation of productivity of 0.023. The persistence and volatility of the uncertainty shock, ρ_σ and σ_σ, are set equal to those estimated by Leduc and Liu (2016) using a structural vector autoregressive model (SVAR), and are given by 0.76 and 0.392 respectively.

We deviate quite sharply from Leduc and Liu (2016) in some of the parameters governing wage setting. In particular, as discussed in section 2.3.1 we adopt an alternative offers framework as opposed to conventional Nash bargaining, which necessitates an alternative calibration strategy. Nevertheless, we aim to align our work as closely as possible with theirs. Thus, we choose the bargaining weight ω of firms and workers to be equal to 0.5, which is also the value used in Leduc and Liu (2016). Moreover, given a steady state value of labor market tightness of $\theta = 0.848$, the free entry condition in equation (24), alongside with the previously calibrated parameters, pins down the steady state asset value, J. Together with a steady-state inverse markup equal to $x = (\eta - 1)/\eta$, and a normalized steady state value of labor productivity $z = 1$, equation (8) determines the steady state wage, w. Thus, in our alternating offers arrangement, the strike value, χ, is then immediately pinned down by the steady-state version of the wage relationship (25) as $\chi = (w - \omega xz)/(1 - \omega) = 0.855$. Thus we target the same steady state wage as that of Leduc and Liu (2016), and thereby also the same profit margin of firms.

Nevertheless, it should be noted that this parameterization implies a small "fundamental surplus" (see Ljungqvist and Sargent (2017)), which is equal to $xz - \chi$. Indeed, this surplus is almost exactly equal in value to that implied by the calibration proposed by Hagedorn and Manovskii (2008), and designed to match the empirical cyclical volatility of unemployment and vacancies.[16] In addition, the steady-state wage elasticity to labor productivity is given by $\omega \times x = 0.45$, which is very close to the value of 0.47 for the post-war US data reported by Petrosky-Nadeau *et al.* (2018, p. 2220)..

2.6.2 Solution Method

We solve the model by a third-order perturbation method using the pruning algorithm by Andreasen *et al.* (2018). There are three reasons underlying this choice: First, a perturbation method of at least the third order is necessary to obtain policy functions that contain volatility shocks as independent

[16]Specifically, the steady-state elasticity of labor market tightness with respect to productivity, which is crucial in determining the magnitude of dynamic changes in the model, is equal to $\eta_{\theta,z} = xz/[\alpha[(xz - \chi)] = 41.28$. In Section 3.4, we examine the sensitivity of our numerical results for combinations of ω and χ that generate smaller values for $\eta_{\theta,z}$.

Table 1: Calibrated parameters

Parameter	Interpretation	Value	Source/steady state target
γ	Coefficient of relative risk aversion	1	Convention
β	Discount factor	0.99	Annual real interest rate of 4%
ψ	Efficiency of matching	0.645	Unemployment rate of 6.4%
η	Elasticity of substitution	0.645	Markup of 11%
δ	Separation rate	0.1	JOLTS database
ω	Workers bargaining power	0.5	Leduc and Liu (2016)
α	Elasticity of $f(\theta)$	0.5	Petrongolo and Pissarides (2001)
κ	Vacancy posting cost	0.14	2 percent of steady state output
Ω_p	Price adjustment cost	112	Leduc and Liu (2016)
ϕ_π	Taylor rule parameter for inflation	1.5	Taylor principle/Convention
ϕ_y	Taylor rule parameter for output	0	Convention
χ	Utility while delaying bargaining	0.85	Steady-state wage relation
ρ_z	Persistence of productivity	0.9	Shimer (2005)
ρ_σ	Persistence of uncertainty	0.76	Leduc and Liu (2016)
σ_z	St. dev. of productivity shock	0.01	Shimer (2005)
σ_σ	St. dev. of uncertainty shock	0.392	Leduc and Liu (2016)
Π	Steady state inflation rate	0.005	Annual inflation rate of 2 percent

Notes. This table lists the parameter values of the model. The calculations and targets are described in the main text. One period in the model corresponds to one quarter.

arguments; that is, a third-order approximation allows the second moment of both exogenous and *endogenous* variables to affect expectations. Second, a third-order perturbation (or higher) allows us to consider the asymmetric effects that are intrinsic to search-and-matching frameworks such as the one considered here (see, for instance, Petrosky-Nadeau and Zhang (2017)). Third, as a third-order approximation is also used in Leduc and Liu (2016) it is straightforward to compare results without concerns regarding computational discrepancies.

For most of our results we will follow Fernández-Villaverde *et al.* (2011) and Born and Pfeifer (2014b) and consider impulse response functions (IRFs) that isolate the *pure uncertainty* effect resulting from higher volatility. That is, we focus on the effect uncertainty has on expectations, and how expectations trickle through to actual decisions, but ignore *materialized* shocks to the *level* of the exogenous processes. As such, we focus on the effect of uncertainty itself, and not on the effect of more extreme realizations of productivity shocks. To be more precise, let $f(\cdot)$ represent the policy function for, for instance, employment. That is, $n_t = f(n_{t-1}, z_t, \sigma_{z,t})$. The *pure uncertainty* IRF is then given by $n_{t+s} = f(n_{t+s-1}, z, \sigma_{z,t+s})$, for $s = 0, 1, \ldots$ In contrast, the *total volatility* IRF is instead given by $n_{t+s} = E_t[f(n_{t+s-1}, z_{t+s}, \sigma_{z,t+s})]$, for $s = 0, 1, \ldots$

However, while the pure uncertainty IRFs provide a clean insight into how uncertainty *per se* affects the economy, it is not unproblematic. In particular, a nonlinear model's pure uncertainty IRFs may differ from the (rational) expectations path households possess of the same variable, and some insights may therefore be lost. As a consequence, when there is a pronounced divergence between the pure uncertainty IRF and the expectations households form, we illustrate both the pure uncertainty and total volatility IRFs. All IRFs are computed around the ergodic mean in the absence of shocks (EMAS), also known as the risky steady state (e.g. Coeurdacier *et al.*, 2011). Appendix A.5 provides further details.

3 Transmission Mechanisms

To illustrate our main findings we proceed in four steps. First we analyze the model under the assumption of risk-neutrality and flexible prices. This allows us to illustrate some basic results of uncertainty shocks that will assist the subsequent analyses. In particular, we show that there is no option-value channel as claimed in Leduc and Liu (2016), but rather a "Nash wage" channel, and that search-and-matching models generically respond asymmetrically to over the business cycle. Second, confining attention to alternating-offers wages – and thereby abstracting from the Nash wage channel – we proceed by illustrating the transmission mechanism of the model with risk aversion and flexible prices. The primary cause underpinning the contractionary effect of increased uncertainty is a rise in the risk premium on equity, as *future* asset prices negatively covary with the stochastic discount factor. Third, we unveil the mechanisms at play when prices are sticky.

Sticky prices give rise to a demand effect that relate both to prudence in preferences and to the asymmetries inherent in frictional labor markets. Together, these two forces exacerbate the effects observed under flexible prices, rendering the contractionary effect of uncertainty more pronounced. Lastly, we compare the results of uncertainty shocks with those of standard "demand shocks", and show that the former yields a flatter Phillips curve than the latter. The reason is that uncertainty shocks brings forth both a negative demand and supply component, which have opposing effect on inflation.

3.1 The absence of an option-value channel

> *Facing higher uncertainty, the option value of waiting increases and the expected value of a job match decreases, inducing firms to post fewer vacancies, making it harder for unemployed workers to find jobs, and ultimately raising the equilibrium unemployment rate* [...] *Firms refrain from hiring since the possibility of a bad hiring decision may have long-lasting negative consequences ex post.*
>
> Leduc and Liu (2016, p. 32; p. 34)

That is, Leduc and Liu (2016) interpret that an increase in uncertainty has a contractionary effect as it is beneficial for firms to defer entry until uncertainty has resolved; as a result, there are fewer vacancies posted and the unemployment rate rises.[17]

We believe that there are two reasons for this statement to be incorrect. First, the free-entry condition in equation (24) – below repeated for convenience – reveals that expected profits gross of the vacancy posting cost is *zero in all time periods, in all states of the world*,

$$0 = h(\theta_t)J_t - \kappa.$$

Thus, as long as the free-entry condition holds it cannot be beneficial for firms to defer entry as expected profits are zero in the present and at all possible states in the future. So what precisely are firms waiting for?

Second, as option-values do not hinge on investors being risk-averse – indeed, Bernanke's (1983) seminal contribution considers risk-neutral investors – the logic underlying an increased option value should also apply to a situation absent of risk-aversion. Thus, using the asset pricing relation in equation (8) with $\Lambda_{t,t+1} = 1$, $t = 0, 1, \ldots$, together with the wage-setting in equation (25), assuming flexible prices such that $x_t = x$, and iterating forward while ruling out exploding paths

[17] Indeed, in relation to the literature the contribution is described as: "However, to our knowledge, our emphasis on the interactions between the option-value channel and the aggregate-demand channel for the transmission of uncertainty shocks is new to the literature" (Leduc and Liu, 2016, p. 22).

gives[18]

$$J_t = (1-\omega)\sum_{s=0}^{\infty}[\beta(1-\delta)]^s E_t\left[xz_{t+s}-\chi\right].$$

As this equation is linear in labor productivity, z_{t+s}, a mean-preserving spread *cannot affect the asset value*.

Figure 1a illustrates this point numerically. The dashed lines show the effect of an uncertainty shock under risk neutrality, flexible prices, and under the benchmark alternating offers wage specification. In accordance with the reasoning above, there is no effect on the economy. The solid lines, however, show the effect of the same shock but under Nash bargained wages. Under this seemingly innocuous alteration of wage-setting, a small but non-trivial recession materializes. Moreover, both wages and asset values fall, which appears contradictory as lower wages ought to increase the match value rather than to decreases it.

Figure 1b reconciles these contrasting dynamics. The dashed line illustrates the total volatility effect of both labor market tightness and wages in period t; or equivalently the (rationally) expected path of these variables from period t onwards. The solid, shaded, lines provide the same illustrations but with expectations formed in periods $t+1$, $t+2$, and so on. As is apparent from the graph, wages are *anticipated* to increase quite markedly in the future, which push down asset values, reduce entry, and generate a recession already in the present.

But to some extent this just begs the question. Why are wages anticipated to rise, and why do they actually – at least in the absence of any materialized shocks – decrease? To address the first point, recall the free-entry condition in equation (24), which is rewritten below using the functional form specified in section 2.6 and some simple algebraic manipulations

$$\theta_t = \left(\frac{\psi}{\kappa}J_t\right)^{\frac{1}{1-\alpha}}.$$

Thus, even under the hypothesis that J_t is linear in productivity and thereby unaffected by a mean preserving spread, Jensen's inequality implies that

$$E_t[\theta_{t+s}] > \left(\frac{\psi}{\kappa}E_t[J_{t+s}]\right)^{\frac{1}{1-\alpha}}.$$

That is, ceteris paribus, a mean preserving spread to the future asset value leads to an expected

[18] Ruling out exploding paths implies that

$$\lim_{s\to\infty}[\beta(1-\delta)]^s E_t[J_{t+s}] = 0, \quad t = 0,1,\ldots$$

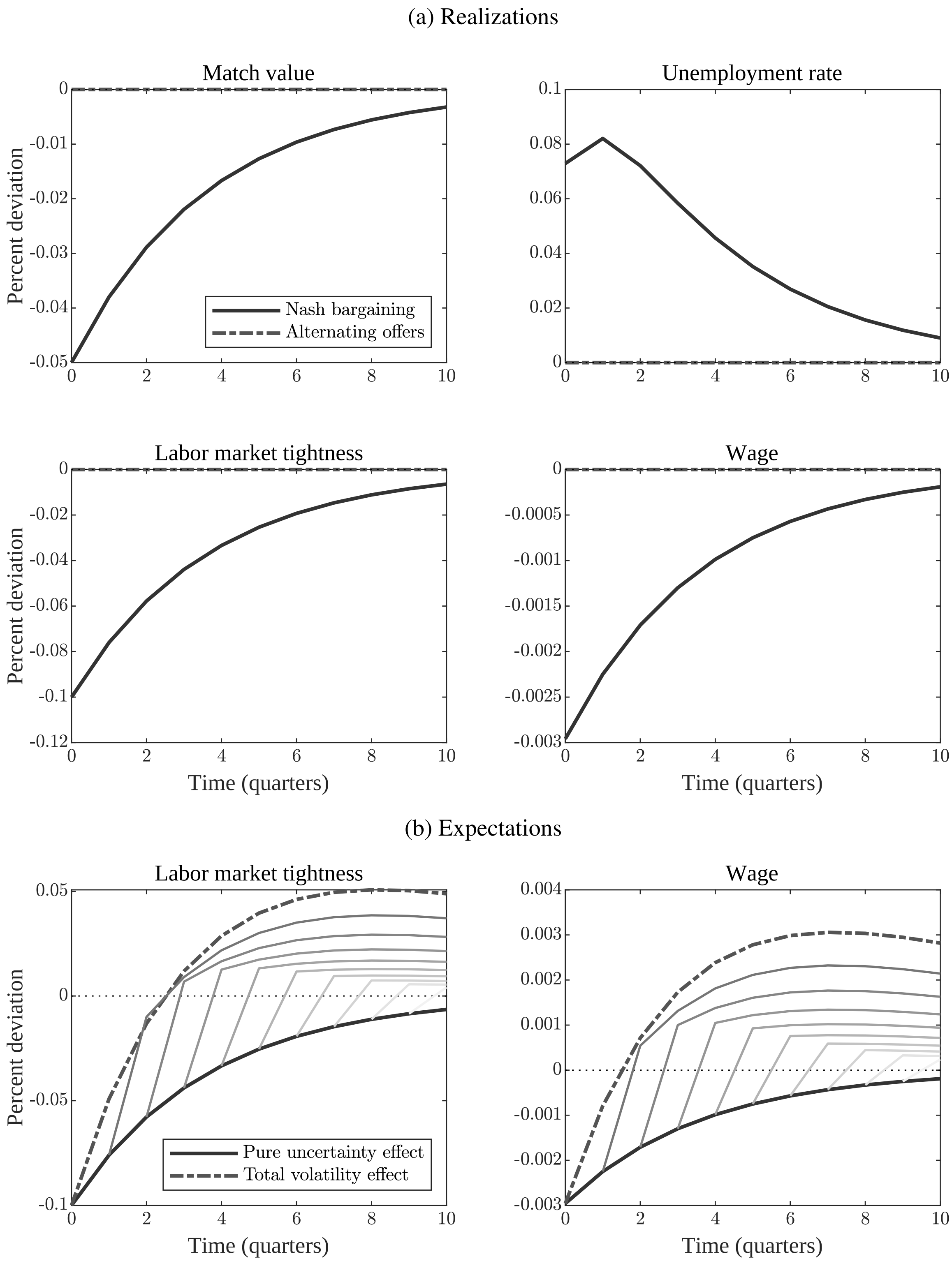


Figure 1: Real Options vs. Nash-Wage Channel

Notes: The two figures illustrate the IRFs for a one standard-deviation shock to volatility under risk neutrality and flexible prices. Panel (b) assumes assumes that wages are set according to Nash bargaining.

increase in the future labor market tightness. Consider again equation (26) which outlines the wages resulting from Nash bargaining

$$w_t^N = \omega x_t z_t + (1-\omega)\zeta + \omega\kappa E_t[\theta_{t+1}].$$

That is, Nash bargained wages are strictly increasing in the expectation of future labor market tightness, and uncertainty therefore puts upward pressure on wages, even if more extreme shocks to productivity actually never materializes. It is the anticipation of their effects that matter, and and as a consequence, wages are anticipated to rise.[19,20]

To address the second point, it is important to observe that uncertainty peaks roughly after seven quarters. Thus, firms in period t anticipate large increases in future wage bills, and both their current and future asset values fall. As a consequence, labor market tightness declines both in the present and in the *near future*, which puts downward pressure on wages in the beginning of the uncertain period.[21] As a result, wages are anticipated to increase, but actually decrease. Proposition 1 formalizes the first of these arguments under some simplifying assumptions.

Proposition 1. *Suppose that productivity is constant, $z_t = z_{t+1} = \ldots = z$, then*

(i) *If wages are set by Nash bargaining $J(z)$ is a strictly concave function, and $\theta(z)$ is a strictly convex function.*

(ii) *If wages are set by alternating offers $J(z)$ is a linear function, and $\theta(z)$ is a strictly convex function.*

Proof. See Appendix A. □

Thus, with risk neutrality, flexible prices and alternating offers bargaining, the economy is entirely unaffected by uncertainty shocks. With Nash bargaining wages, however, Jensen's inequality implies that wages are anticipated to rise, which puts downward pressure on asset values, and thereby renders a recession. The remainder of the paper will abstract from this "Nash-wage channel" for several reasons. First and foremost, adopting alternating offers rather than Nash wages allow us to examine the interaction of search frictions, risk-aversion, and sticky prices in determining the impact of uncertainty shocks in isolation from any confounding effects due to the Nash wage channel. Second, we are not aware of any compelling evidence that suggests that the Nash wage channel is

[19] From a more intuitive point of view, wages are anticipated to rise as the future labor market for unemployed houdholds is expected to improve, shrinking the current surplus for workers, and thereby pushes up wages.

[20] Notice that expected future labor market tightness rises in response to increased uncertainty also under alternative offers wage-setting. The difference is that this increase does not trickle through into current wages, and therefore does not carry any implications for the economy.

[21] Notice that in the short run there is a trade off between the actual *materialized* level level of labor market tightness and its expected value; conditional on the former, the latter increases, but conditional on the latter, the former decreases. Early on, the materialized effect dominates the expected effect, but as uncertainty approaches its peak the roles reverse.

an empirically relevant mechanism to consider in light of uncertainty shocks on unemployment. Put differently, we would tend to interpret these results as a vice rather than a virtue of Nash bargained wages. In view of these considerations, from now on we adopt the linear wage specification in equation (25) and explore how uncertainty shocks transmit to firm hiring activity when households are risk-averse.

Lastly, the law of motion for employment, n_t, is given by

$$n_t = (1 - n_{t-1} + \delta n_{t-1}) f_t + (1 - \delta) n_{t-1},$$

with steady state value

$$n = \frac{f}{f(1-\delta)+\delta}.$$

This lead us to a final proposition with regards to a (somewhat known) asymmetric property of search-and-matching models.

Proposition 2. *Suppose that productivity is constant, $\alpha \leq 1/2$, and $J(z)$ is a weakly concave function; then $n(z)$ is a strictly concave function.*

Proof. See Appendix A. □

Proposition 2 is not a mere mathematical curiosity, but economically meaningful. In particular, the first term in the law of motion for employment is given by $u_t^s \times f_t$. In expansions, the amount of job-seekers, u_t^s, is small and the job-finding rate, f_t, is large – while the opposite is true in recessions. Thus, if the job-finding rate is relatively symmetric over the business cycle, its decline in recessions has a more pronounced effect on employment than its rise in expansions, which, ceteris paribus, leads to a lower expected employment rate in more volatile times. Put somewhat simplistically; good times are simply not as good as bad times are bad.

As both Propositions 1 and 2 reveal steady-state properties, figure 2 numerically illustrate the associated dynamics in response to an uncertainty shock using alternating-offers bargaining. It may appear contradictory that the expected labor market tightness increases in response to an increase in uncertainty, while the expected employment rate decreases.

3.2 The transmission mechanism under flexible prices

Figure 3 shows the results of a one standard-deviation shock to uncertainty under risk aversion and flexible prices, using the alternating-offers wage-setting baseline. In marked contrast to figure 1a, the result is a pronounced decline in economic activity, including a rise in the unemployment rate

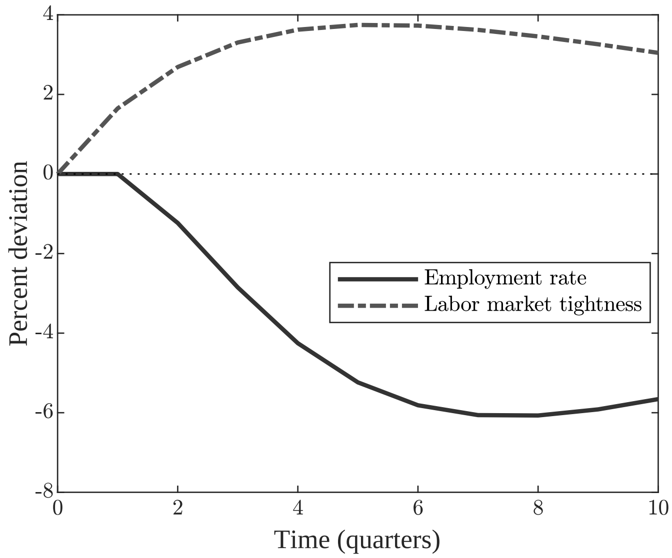


Figure 2: Expected labor market tightness and employment.

Notes: The figure illustrates the total volatility effect of a one standard-deviation shock to volatility under risk-neutrality and flexible prices.

and a reduction in both the inflation- as well as the real interest rate. Importantly, there is also a marked increase in the risk premium on equity. Thus, while the economy recedes, prices for safe asset increase, while those on risky assets decline.

3.2.1 Unemployment

To understand which forces underpin these dynamics, it is instructive to first focus on the "real side" of the economy, and subsequently turn to the interest rate and inflation dynamics. A rise in the unemployment rate is driven by a fall in equity prices. To understand why this happens, notice that we can decompose the equilibrium equity price as

$$\begin{aligned} J_t &= (1-\omega)(xz-\chi) + (1-\delta)E_t\left[\Lambda_{t,t+1}J_{t+1}\right] \\ &= (1-\omega)(xz-\chi) + (1-\delta)\left\{E_t[\Lambda_{t,t+1}]E_t[J_{t+1}] + Cov_t(\Lambda_{t,t+1}, J_{t+1})\right\}, \end{aligned} \tag{29}$$

where the absence of t-subscripts indicate that the relative price of intermediate goods, x_t, is constant, and there are no materialized shocks to productivity, z_t. Thus, the only remaining moving parts are those pertaining to expectations; both of the stochastic discount factor and future asset prices, as well as their covariance.

As shown in figure 3, the risk free real interest rate declines, which implies that the expected stochastic discount factor, $E_t[\Lambda_{t,t+1}]$ increases. This is due to two reasons: First, with preferences

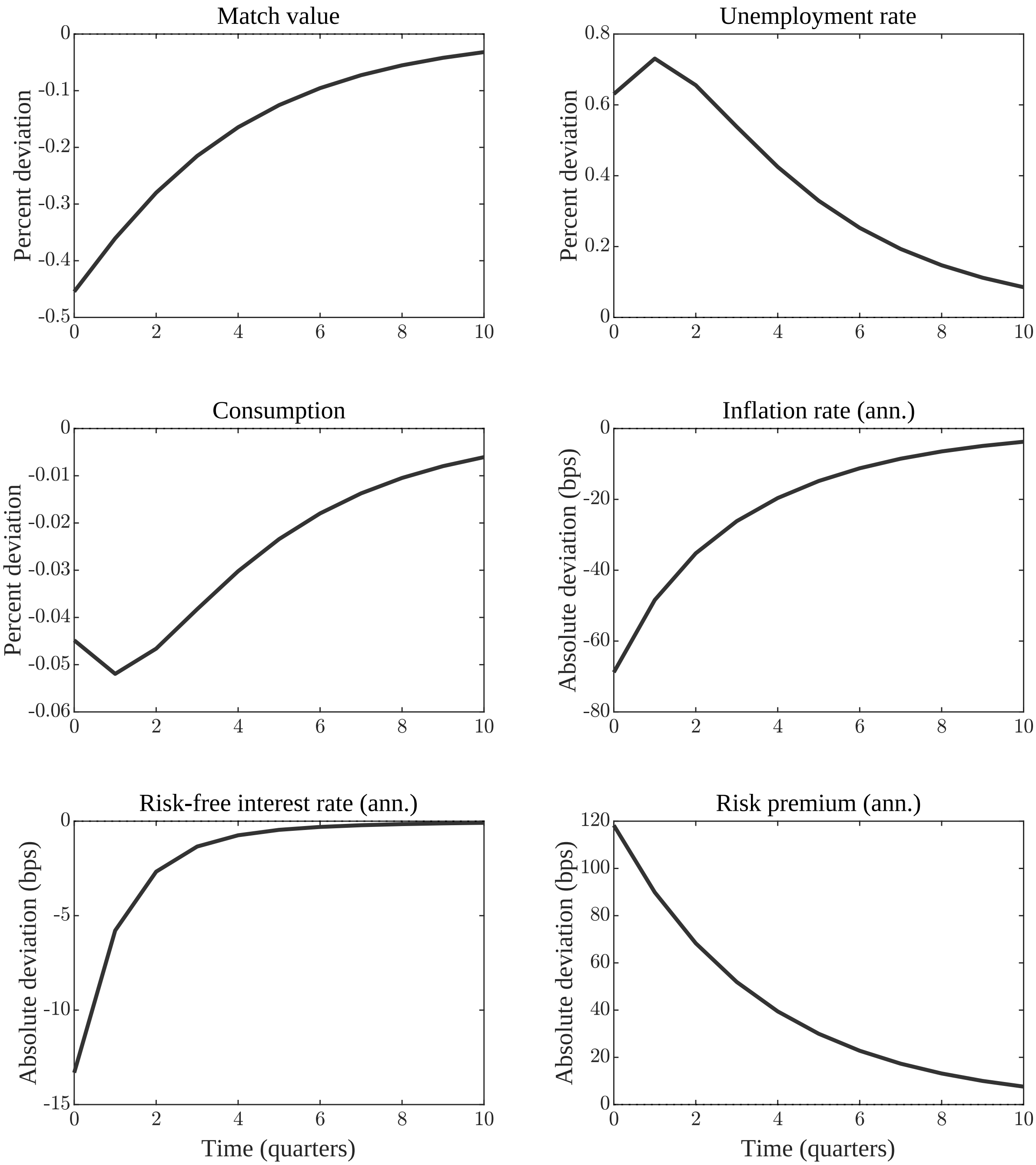


Figure 3: Transmission under Flexible Prices

Notes: The figure illustrates the IRFs for a one standard-deviation shock to volatility under risk aversion and flexible prices.

exhibiting prudence, an increase in uncertainty raises the expected marginal benefits of resources in the future, which sets off a precautionary motive to save. The precautionary motive puts upward pressure on the price of equity. Second, the employment asymmetries outlined in Proposition 2 indicates that a decline in expected future employment is imminent which further reinforces a perceived increase in the marginal benefits of savings through a desire to smooth consumption over time. This adds an additional positive force pressing up the equity price.

Given that both the above-mentioned mechanisms puts positive pressure on equity prices, the third and final force – the covariance term between the stochastic discount factor and the future price of equity – must react negatively. Using the definition of the risk premium in equation (7) together with the decomposed asset price above reveals a tight relationship between the risk premium and the covariance term

$$RP_t = -Cov_t(\Lambda_{t,t+1}, J_{t+1}) \frac{(1-\delta)}{(J_t - d_t)E_t[\Lambda_{t,t+1}]}.$$

Thus, as the risk premium increases, the covariance term declines; and it must decline sufficiently to offset the rise in the expected stochastic discount factor. As a consequence, the main mechanism which brings the economy down is a fall in equity prices brought about through a rise in the risk premium, resulting from decline in the covariance between the stochastic discount factor and future equity prices. Of course, as shocks are persistent, this mechanism is expected to repeat itself in the future, and there is a reinforcing effect arising from an additional anticipated decline in future equity prices, which puts additional downward pressure on current prices, and so on.

This story is not without economic appeal. A rise in uncertainty brings about a motive to save; both because of prudence, and the non-linear dynamics of employment. This enhanced motive to save would, in isolation, put upward pressure on equity prices and result in an expansion. However, as consumption and asset prices are positively correlated, there is a negative covariance between future asset prices and the stochastic discount factor, indicating that equity indeed is a poor asset for hedging against this increase in risk. This latter aspect leads to a rise in the risk premium which brings down the equity price. If this latter channel dominates the former – which it does under the baseline calibration – the result is an increase in unemployment alongside a rise in the risk premium.

To provide a quantitative account for these mechanisms, the left-most part of figure 4 shows a decomposition of the cumulative rise in unemployment along the IRF. To conduct this decomposition, we first solve the model using equation (29) but *suppressing the covariance term to be zero*. The difference between the baseline result and the outcome of this exercise is due to the dynamics of the risk premium. As can be seen from the figure, the rise in risk premium puts significant upward pressure on the unemployment rate. Second, we repeat the above exercise, but additionally using a *linear approximation of the marginal utility* around the stochastic steady state value of consumption.

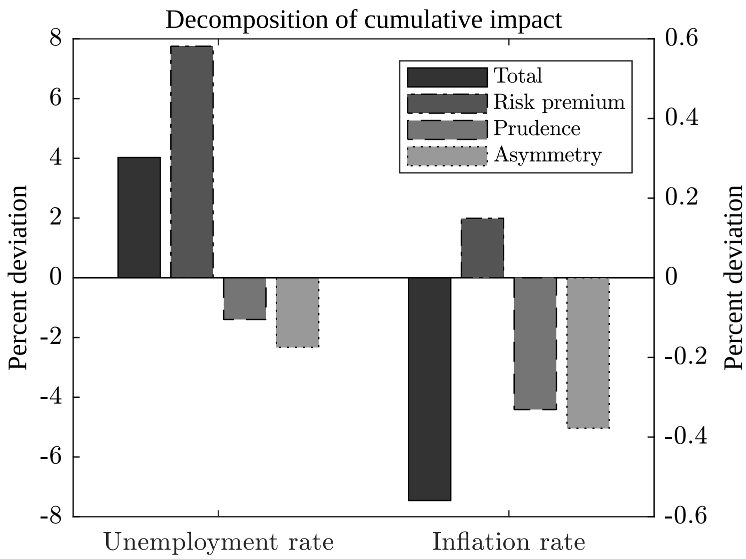


Figure 4: Decomposition of effects.

Notes: The figure illustrates the cumulative effect of the various transmission mechanism on two macroeconomic aggregates: unemployment (left axis) and inflation (right axis). The computations are described in the main text.

As a linear marginal utility exhibits certainty equivalence, the difference between this exercise and the previous accounts for the effect of prudence. Figure 4 reveals that prudence brings forth a negative, stabilizing, effect on the unemployment rate. Lastly, absent both prudence and the risk premium, the remaining dynamics are those pertaining to the non-linearities in the law of motion of employment, and reflect the asymmetries inherent in search-and-matching models. Again, these asymmetries gives rise to an additional negative effect on the unemployment rate.

3.2.2 Inflation and interest rates

While the movements in both inflation and the interest rate are immaterial in a flexible price setting, understanding their dynamics will prove useful to unveil the mechanisms at play in the presence of nominal rigidities.

As outlined in the previous section, an increase in uncertainty renders a decline in the risk free real interest rate as both prudence and employment asymmetries push up the expected stochastic discount factor, $E_t[\Lambda_{t,t+1}]$. This movement in the risk free rate stands in marked contrast to the returns on equity which increase due to the rise in the risk premium. While a reduction in the risk free interest rate can materialize both due to a decline in the nominal rate, or because of a rise in *expected inflation*, the Taylor rule in equation (27) reveals that the nominal rate will only be lowered if there is a reduction in *current inflation*. Thus, the real interest rate falls as the nominal interest rate declines more than expected inflation, which leads to a reduction in the nominal rate that is sufficiently pronounced to outweigh the perceived decline in future inflation.

However, movements in the risk premium is not unimportant to this story. In particular, as the risk premium rises, equity prices fall, the unemployment rate increases, and current private consumption declines. As a consequence, the rise in the expected discount factor is therefore less pronounced than it would be in the absence of a risk premium, and the fall in both the nominal interest rate and inflation is therefore somewhat muted.[22] As will become apparent, this mechanism will give rise to a flatter Phillips curve than would be observed under regular demand shocks (see Section 4.1).

Lastly, following the same logic as in the previous section, figure 4 decomposes the cumulative response to inflation into its three driving forces. As anticipated, both prudence and employment asymmetries contribute to a fall in inflation, while the risk premium is indeed inflationary. However, in the baseline setting the two former effects dominates the latter, and there is an overall decline in inflation.

3.3 Transmission under Sticky Prices

Figure 5 shows the results corresponding to figure 3 but with sticky prices. Notice that the graph containing the risk premium has been replaced by the relative price of intermediate goods, x_t.[23] As can be seen from the figure the qualitative results line up with those of figure 3, but they are quantitatively more pronounced; equity prices fall by almost 4 percent, and the unemployment rate increases by almost 5 percent. Thus, several measure of economic activity are magnified by almost an order. The reason is that two of the previously stabilizing forces – prudence and the employment asymmetries – are now destabilizing.

The reason nominal rigidities destabilize these forces follows a familiar new-Keynesian narrative. The rise in uncertainty puts upward pressure on the expected stochastic discount factor and thereby downward pressure on the risk free real interest rate. However, as the monetary authority is constrained in its reaction by the Taylor rule, the nominal interest rate does not change unless there is visible deflation. Thus, absent deflation the real interest rate would be left unchanged, and demand for final goods would fall short of supply. The reduction in demand, however, encourages retail firms to lower their prices. But because of price-adjustment costs their response is muted, which results in a decline in demand for, and price of, intermediate goods, x_t. As a consequence, the equity price falls, there is less entry, less production, and supply approaches the reduced level of demand. At the same time, the reduction in the price-level leads to deflation and thereby a reduction in real and nominal interest rates, which mute the initial fall in demand. This process ends when

[22] Another, more heuristic, way of seeing this is that the movements in the covariance term in equation (29) is akin to a negative supply shock, which are commonly associated with inflationary pressure.

[23] We will return to the dynamics of the risk premium in Section 4.1.

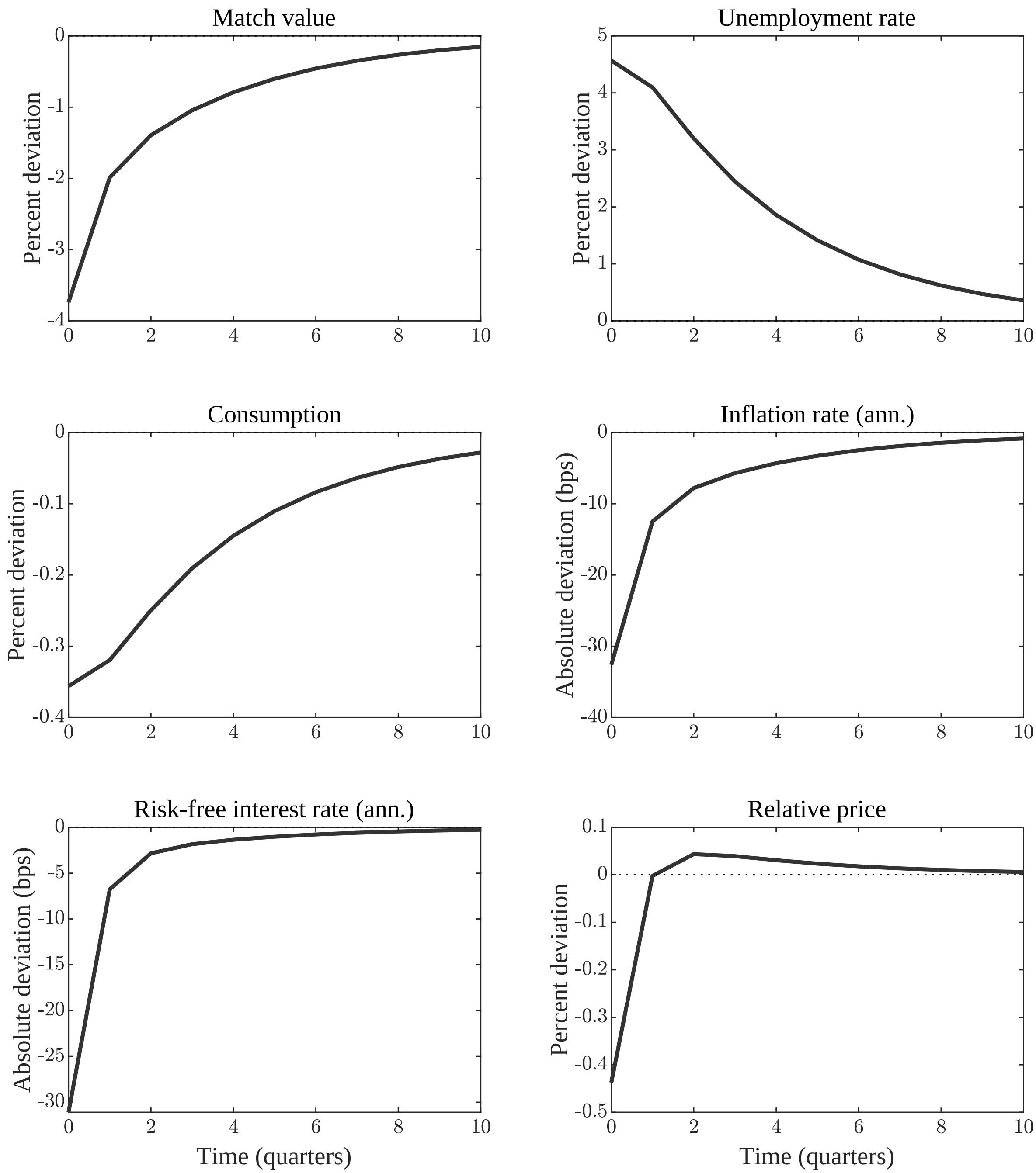


Figure 5: Transmission under Sticky Prices

Notes: The figure illustrates the IRFs for a one standard-deviation shock to volatility under risk aversion and sticky prices.

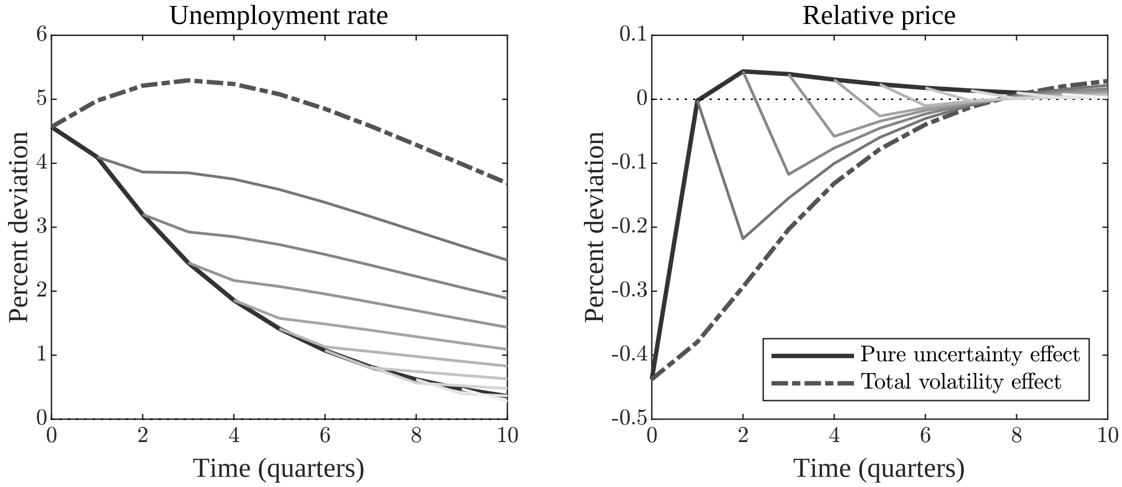


Figure 6: Unemployment and relative price expectations

there is an equal decline in both the demand and supply for goods, and the equilibrium is restored. In contrast to the case with flexible prices, the equilibrium equity price is now lower partly as a result of a decline in the relative price for intermediate goods, which is driven by demand, and partly as a result of an increase in the risk premium. Thus, the same mechanisms that stabilized the eco nomy under flexible prices – those that put upward pressure on the expected stochastic discount factor – are now, via the demand channel, destabilizing.

There are a few nuances, however, to this story that deserves to be highlighted. First it may appear surprising that a seemingly short-lived decline in the relative price of intermediate goods can lead to such a dramatic increase in the propagation of shocks. It does not. Indeed, figure 6 reveals that the agents *expect* relative prices to remain depressed for an extended period of time. The reason is that the employment dynamics asymmetries outlined in Proposition 2 leads agents to anticipate further adverse demand consequences in the future, which provides the foundation for an outlook of a persistently depressed relative price. And as the equity price is forward looking, an expected, persistent, decline in the relative price puts severe negative pressure on the equity price already in the present. Thus, the employment asymmetry which is immaterial under risk-neutrality – and indeed stabilizing with risk aversion and flexible prices – now gives rise to a demand asymmetry with negative consequences on economic activity.

Second, the inflation rate and the risk free interest rate display quite different dynamics than under flexible prices. More precisely, inflation declines by less, while the risk free rate declines by more. This is because flexible prices allows for larger adjustments in the inflation rate, which leads to a pronounced decline in *expected inflation*. Thus, when prices are flexible, the inflation rate declines markedly on impact, and is also expected to decline even further. As a consequence, while the nominal interest rate reacts according to the Taylor rule, the real interest rate falls by less under

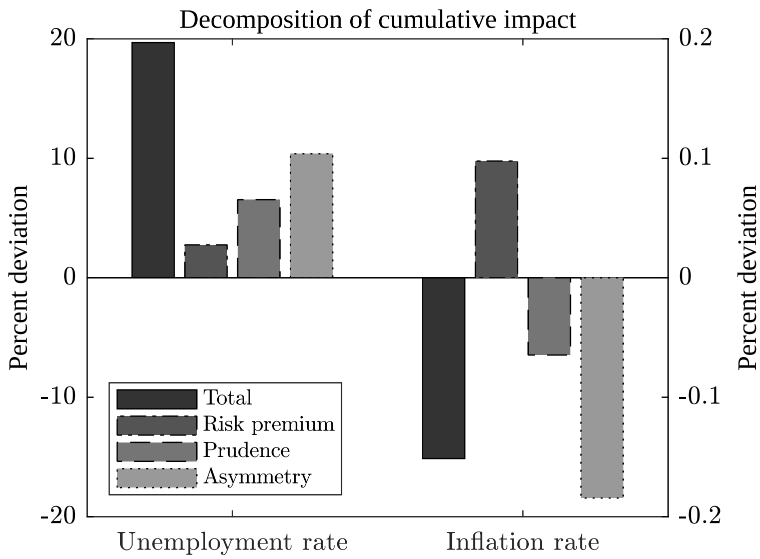


Figure 7: Decomposition of effects

Notes: The figure illustrates the cumulative effect of the various transmission mechanism on two macroeconomic aggregates: unemployment (left axis) and inflation (right axis). The computations are described in the main text.

flexible prices as inflation is *expected* to remain low for a considerable amount of time.[24]

Lastly, absent of uncertainty shocks, sticky prices commonly underpin a stabilizing force when the economy is exposed to productivity shocks *in levels*. The reason is that a negative productivity shock leads to a decline in supply of intermediate goods that, absent any price movements, exceeds that of demand. As a consequence, the relative price of intermediate goods, x_t, increases, and retail firms raise their prices. The result is a rise in inflation and the real interest rate, and, as x_t increases, a decline in employment that is muted relative to the flexible price outcome. As this logic is not violated in our setting, one may wonder why sticky prices propagate, instead of dampen, the effects of "productivity-shock uncertainty". There are two reasons. First, while sticky prices dampen the movements in economic aggregates due to productivity shocks, they do not eliminate them. Thus, uncertainty still matters, and with an uncertain future, price rigidities amplifies the effect in the present. Second, as the uncertainty shock is persistent, there is an anticipation of a repetition of the decline in current economic activity also in the future – albeit somewhat less pronounced – which makes the uncertainty shock even more detrimental.

Figure 7 provides some additional results pertaining to this reasoning. In particular, the figure illustrates the decomposition described in section 3.2, which was illustrated in figure 4, but now under sticky prices. While the decomposition is less transparent in the current setting, as each mechanism is itself interacted with the nominal rigidities, there are a few lessons to be learnt from this exercise.

[24] Recall that the real interest rate is determined by the nominal rate and expected, rather than current, inflation.

First, and foremost, both the precautionary motive, due to the increase in uncertainty, and the motive to intertemporally smooth consumption, because of the asymmetric employment dynamics, are now operating in the *opposite* direction compared to the flexible prices benchmark. The reason why is outline in detail in the beginning of this section, and hinges on the demand effect the arises due to nominal rigidities; what were previously stabilizing forces are now destabilizing.

Second, the risk premium still contributes to the decline in economic activity, but its effect on unemployment is eclipsed by the demand side effects arising from both the precautionary motives as well as the desire to intertemporally smooth consumption.

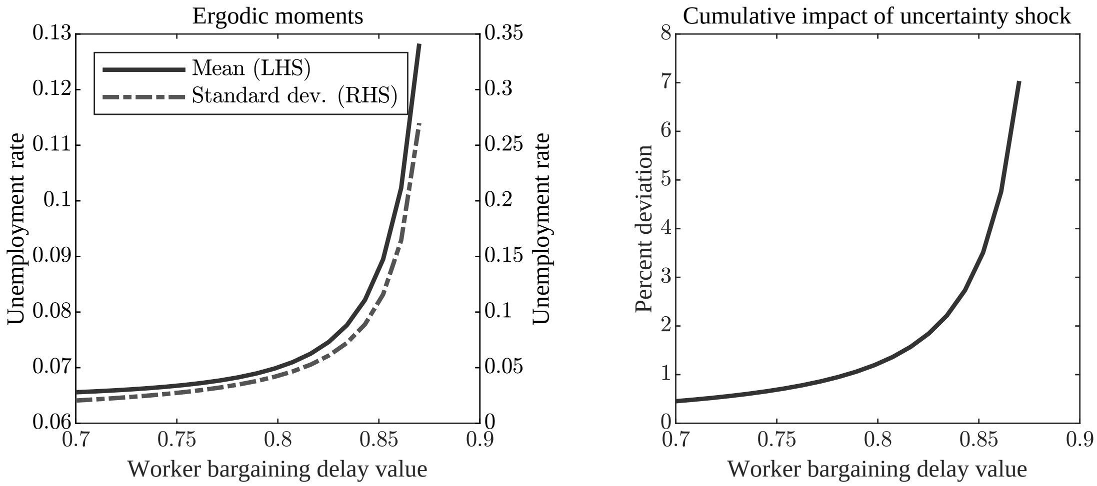
Lastly, the inflationary pressure stemming from the increase in the risk premium remains positive and significant. The reason is that the shortfall in demand must, in equilibrium, be met by an equal shortfall in supply. Under the standard new-Keynesian logic the latter happens through reduction in retail prices that leads to a decline in the relative price of intermediate goods, x_t, which in turn contracts supply. This process continues until the equilibrium is restored. In the current setting, however, supply contracts even in the absence of any movements in the relative price, x_t. The reason is that as the risk premium rises, asset prices fall, entry of intermediate good declines, and there is less supply of intermediate goods even in the absence of relative price adjustment. As a consequence, there is less need for the economy to operate through other prices margins – including retail and intermediate goods prices – and the deflationary pressure is therefore suppressed. As we will see, this latter feature gives rise to some dynamics that distinguishes uncertainty shocks from more conventionally modeled aggregate demand shocks.

3.4 Robustness

In general, the extent to which a search and matching model is able to replicate the significant volatility of employment as well as other macroeconomic variables depends heavily on the elasticity of labor market tightness with respect to productivity, $\eta_{\theta,z}$, which in turn is primarily determined by the size of the fundamental surplus fraction $\frac{xz}{xz-\chi}$ (Hall, 2005; Hagedorn and Manovskii, 2008; Ljungqvist and Sargent, 2017) as $\eta_{\theta,z} = \frac{1}{\alpha}\frac{xz}{xz-\chi}$. Likewise, whether or not uncertainty shocks cause mild or severe recessions in the New Keynesian model with labor market frictions depends not only on the degree of risk aversion (on which see below) or whether prices are flexible or sticky (and if so, how rigid they are) but also, and crucially, hinges on the value of parameter χ which represe

In particular, only if employment is sufficiently volatile (i.e., χ and, hence, $\eta_{\theta,z}$ ar high) will a mean-preserving spread to productivity shocks in conjunction with the intrinsic non-linearities of the SaM model lead agents to downgrade their expectations for future employment by a significant amount. In our baseline calibration, we sought to stay as close as possible to Leduc and Liu (2016), which implies a relatively high value of $\eta_{\theta,z}$, equal to approximately 41. Figure 8 explores the

(a) Flexible prices



(b) Sticky prices

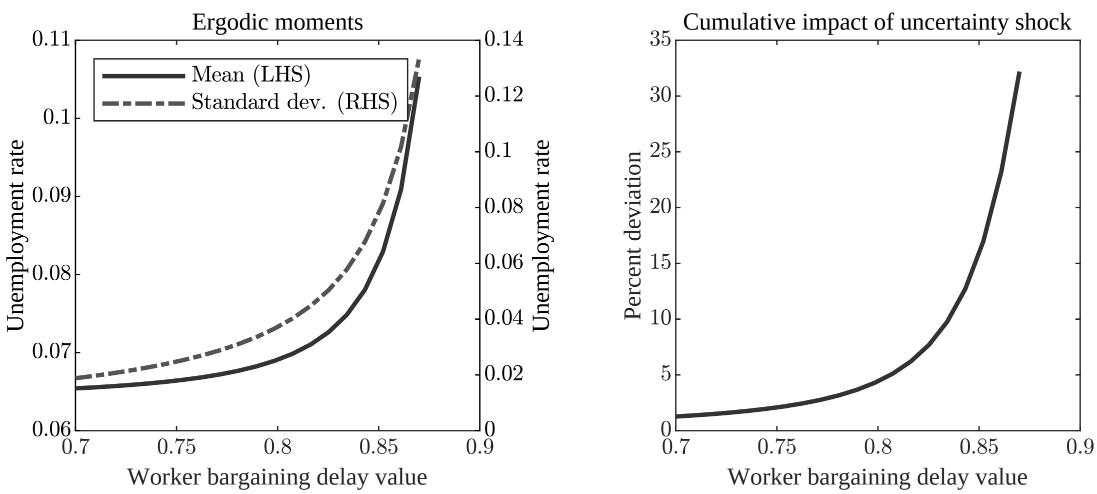


Figure 8: Sensitivity Analysis

Notes: This figure shows the impact of business cycle volatility on the mean and standard deviation of the unemployment rate (left-hand panel) and the cumulative effect of a pure uncertainty shock (right-hand panel) as a function of the worker bargaining delay value χ. Model specification: log utility, linearized NKPC, $\phi_\pi = 1.5, \phi_y = 0$.

sensitivity of results to the choice of the bargaining parameter χ under both flexible (panel 8a)and sticky prices (panel 8b). The implications are displayed in terms of the first and second ergodic moments, as well as the cumulative effect of an uncertainty shock, using the unemployment rate as the variable of interest in both instances. A first key takeaway is that if χ is smaller than the benchmark value of 0.85, then the standard deviation of unemployment becomes smaller. This means that the degree to which employment asymmetries push the ergodic mean of unemployment above the steady-state rate of 0.064 is lessened. The effects of a pure uncertainty shock are likewise less severe. This is true both in the absence of sticky prices (where the risk premium effect becomes stronger for larger values of χ) and with nominal rigidities added to the model (in which case demand effects also become worse). Conversely, an even larger parameter value leads to discontinuously more extreme results. A second important point that emerges from a comparison of the upper and lower panels is to underscore the idea that sticky prices can *destabilize* the economy conditional on volatility shocks even when they have a *stabilizing* effect in a setting without nominal rigidities. Appendix A.4 explores the sensitivity of the results documented in the main text along several additional dimensions.

4 Implications

4.1 Uncertainty shocks are not (just) aggregate demand shocks

A cursory reading of figure 5 suggests that uncertainty shocks affect economic activity no differently from regular (aggregate) demand shocks, such as contractionary monetary policy. Indeed, both inflation and the risk free real interest rate declines, output contract and the unemployment rate rises. So can uncertainty shocks be distinguished from demand shocks?

To address this issue we modify the Taylor rule in equation (27) to include a shock to monetary policy, and reverse engineer a persistent rise in the nominal interest rate such that the impulse response function of unemployment *exactly* coincides with that of figure 5. That is, the sequence of interest rate shocks are such that the resulting effect on real economics activity is identical to that resulting from an uncertainty shock. The effect on inflation and on the risk premium is documented in figure 9, and as can be seen from the figure, uncertainty shocks have a relatively muted effect on inflation, and a much more pronounced effect on the risk premium.

The reason is quite straightforward. An interest rate hike reduces demand for final goods through the Euler equation. Facing lower demand, retail firms reduce their prices, leading to an overall decline in the price level. As prices are sticky, however, the resulting price-adjustment is incomplete, and retailers demand fewer intermediate goods. As a consequence, the relative price of intermediate goods, x_t, falls, which then contracts supply. This process continues until the (goods) market is in

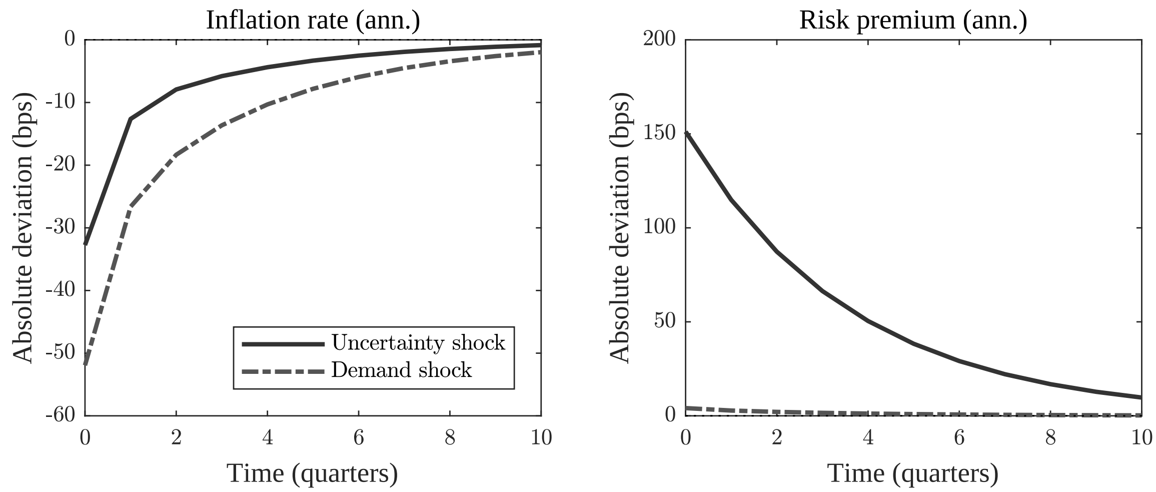


Figure 9: Uncertainty vs. demand shocks

Notes: IRFs for a one-standard deviation shock to $\varepsilon_{e_R,t}$ and $\sigma_{e_z,t}$, respectively. Units are in deviations from stochastic steady-state (SSS). Model specification: CRRA utility ($\gamma = 3$), sticky prices, linearized NKPC, $\phi_\pi = 1.5$, $\phi_y = 0$. The impulse response for the demand shock is computed as a representative GIRF in the sense that future shock realizations are averaged out.

equilibrium, at a lower level of economic activity.

An uncertainty shock operates through similar mechanism with one pronounced difference: as the risk premium increases, asset values fall even without any adjustment to the relative price, x_t. This contracts entry, hiring, and reduces the supply of intermediate goods. Thus, in order to restore the equilibrium, there are less pronounced price-adjustments (and therefore less deflation), and a less pronounced decline in the relative price, x_t. Put simply; deflation materializes to bring supply towards demand. But as an uncertainty shock contracts supply even in the absence of any price movements, less deflation is needed to bring the markets back to equilibrium.

Because uncertainty shocks combine features of demand shocks (resulting from the interaction of households' precautionary savings with sticky prices) with supply features (originating in movements of the risk premium attached to firm equity), an economy hit by uncertainty shocks will display a Phillips curve relationship that appears flatter than the same economy subject to demand shocks. To illustrate, Figure 10 shows scatter plots of realizations in unemployment and inflation for an economy simulated over 1,000 periods. Specifically, panel a) describes an economy that is subject only to normally distributed innovations to the policy rate; all other shocks are shut down. Each dot then represents a pair (u_s, Π_s^{ann}) for one period s. To facilitate direct comparison, and because interest rate shocks tend to have disproportionately stronger effects on the economy than uncertainty shocks in this model, we scaled average shock sizes such that the implied standard deviation of unemployment is equal across both cases.[25] As predicted, the simulations show that

[25] It is very common in this class of theoretical models that level shocks are propagated to endogenous variables with

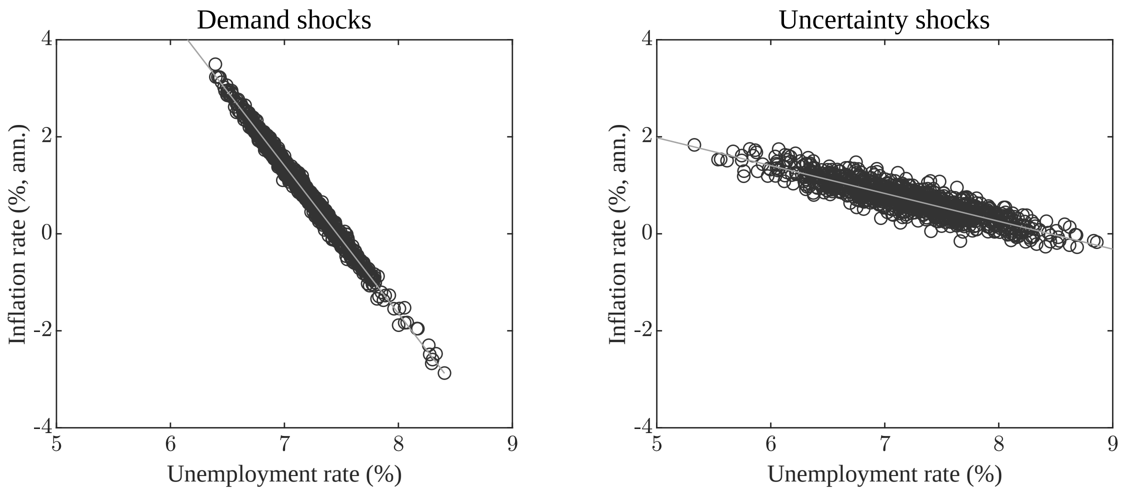


Figure 10: Phillips curve relationship under demand and uncertainty shocks

Notes: Model specification: log utility, sticky prices, linearized NKPC, $\phi_\pi = 1.5$, $\phi_y = 0$. In the (left-hand) right-hand panel, realizations of shocks to the level (volatility) of interest rates are suppressed for expositional purposes. Results are based on simulation of 1000 periods.

the Phillips Curve implied by uncertainty shocks implies changes in the unemployment rate to be associated with smaller variations in inflation than is the case following demand shocks. Another way of making the same point is that the volatility of inflation *relative* to that of unemployment is 0.37 in the case of level shocks to the interest rate, whereas it is lower for uncertainty shocks at 0.17.[26]

4.2 The role of monetary policy

The analysis in Section 3.3 suggests that uncertainty shocks appear to cause a sizeable recession in the theoretical model once we allow for the interaction of search frictions, risk-aversion, and nominal rigidities.[27] Yet at least under our benchmark specification of the model, a central bank that is responsive not only to inflation variability but also to output deviations, as indicated by a parameter value $\phi_y > 0$ in the Taylor rule, can dramatically reduce the severity of the economic contraction. This result is for two reasons, but also subject to major qualification.

The first reason is that $\phi_y > 0$ directly implies a more accommodative policy stance given the contraction in output in the present. Second, and crucially, such a perturbation of policymakers' reaction function also affects the formation of beliefs that we have argued throughout this article are

greater amplification than is the case for second-moment shocks. We elaborate on this point in the concluding Section 5.

[26] This pattern is not an artifact of differences in the persistence of shocks. If we set both ρ_{e_R} and $\rho_{\sigma_{e_R}}$ equal to 0.95, then $\sigma_\Pi/\sigma_u = 0.57$ for the case of level shocks and 0.18 for the case of uncertainty shocks.

[27] To put the results in Figure 5 into perspective, Leduc and Liu (2016, Fig. 2) report VAR evidence that a one-standard-deviation increase in consumer uncertainty leads to a peak increase of unemployment to the amount of approximately 2.55 percent relative to the sample average.

crucial in determining the effects of uncertainty shocks. The key premise here is that, as Lepetit (2019, esp. Fig. 2 and Fig. 3) demonstrates, in a model like ours the central bank faces a tradeoff between inflation volatility and mean employment. To see this, notice first that the direct impact of a positive productivity shock is to increase the supply of intermediate goods for any given level of employment. Keeping aggregate demand constant, this pushes down the intermediate price of inputs x or, equivalently, markups rise. At the same time, however, the shock increase incomes and hence stimulates the demand for (ultimately) intermediate goods, putting upward pressure on x. The reverse holds true for negative productivity shocks. By responding to output ($\phi_y > 0$), policymakers can limit the second effect and, thus, engineer procyclical markups, dampening business cycle volatility in hiring. Given the asymmetric employment dynamics of the model, this also implies that the "employment gap" caused by business cycle volatility is smaller in absolute magnitude. Returning to the impact of uncertainty shocks, greater values of ϕ_y thus reduce the force of the asymmetry-demand channel.

Figure 11 illustrates this idea by contrasting the benchmark specification (black-solid) to a variant that only differs in that $\phi_y = 0.2$ rather than $\phi_y = 0$ (dark-dash-dotted): the recession triggered by the volatility shock is much less severe.

The preceding observations about monetary policy are subject to the important qualification that we assumed, thus far, that the price adjustment costs paid by retailers, denoted

$$ac_t = \frac{\Omega_p}{2}\left(\frac{\Pi_t}{\Pi} - 1\right)^2 y_t,$$

are "virtual" in the sense of affecting their optimal price-setting choices yet without requiring real resources to be expended (cf. Subsection 2.2.2). Supposing otherwise and accordingly modifying the resource constraint to read

$$c_t = z_t n_t - ac_t,$$

turns out to introduce a quantitatively significant additional transmission channel as well as confront policymakers with a difficult choice when deciding on how to react to uncertainty shocks.[28] Two observations stand out. First, the recession is deeper for any given specification of monetary policy behavior as compared to the benchmark case where $c_t = z_t n_t$ – comparing the black-solid and medium-dashed lines makes this point for the example of $\phi_y = 1.5$, $\phi_y = 0$. This is because the expected increase in technological volatility leads households to also expect greater variability in inflation. Given a quadratic price adjustment cost, households consequently expect future resources

[28]To be clear, we reckon it unlikely that this feature is considered desirable by users of a model like ours (or comparable ones), but believe that it is important to be aware of it given its quantitative significance.

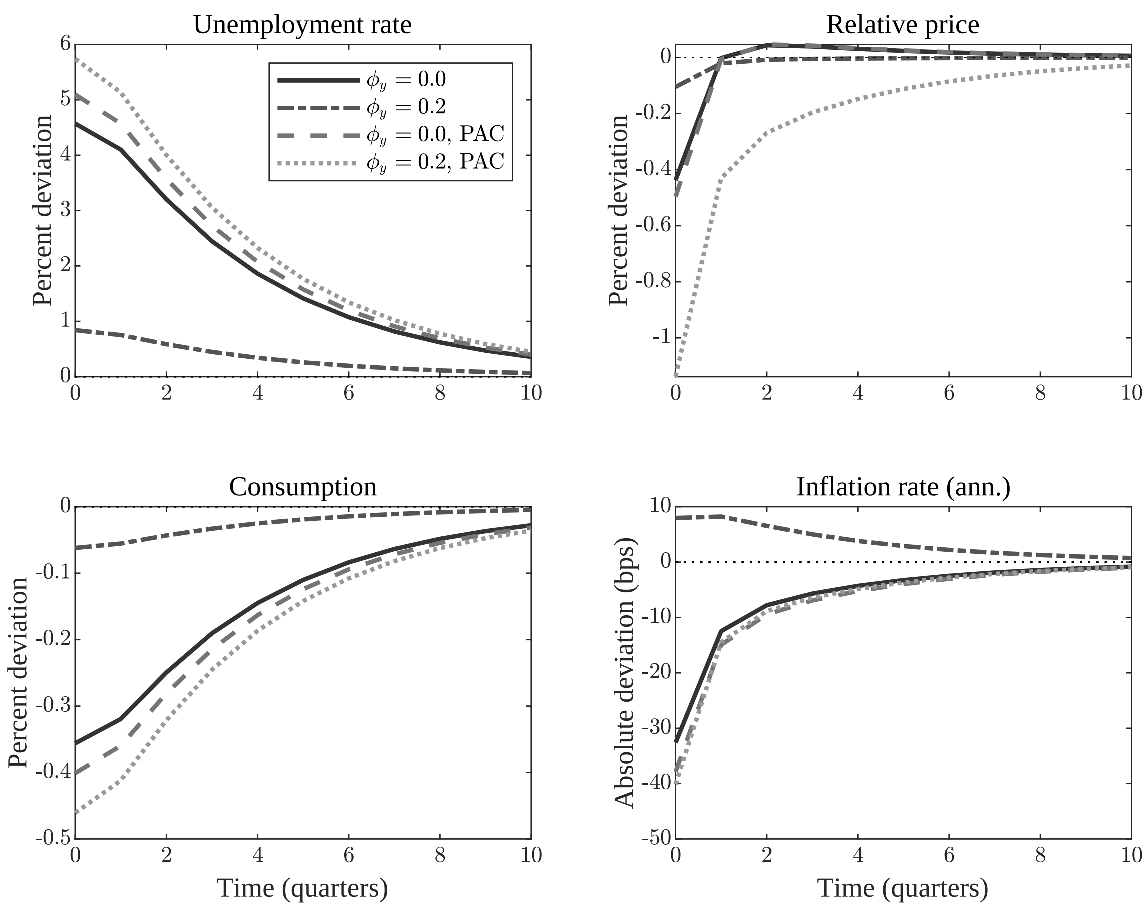


Figure 11: Role of monetary policy & price adjustment costs

Notes: IRFs for a one-standard deviation shock to $\sigma_{z,t}$. Units are proportional deviations from stochastic steady-state (SSS). Model specification: log utility, sticky prices, linearized NKPC. "PAC" stands for price adjustments being costly in resource terms.

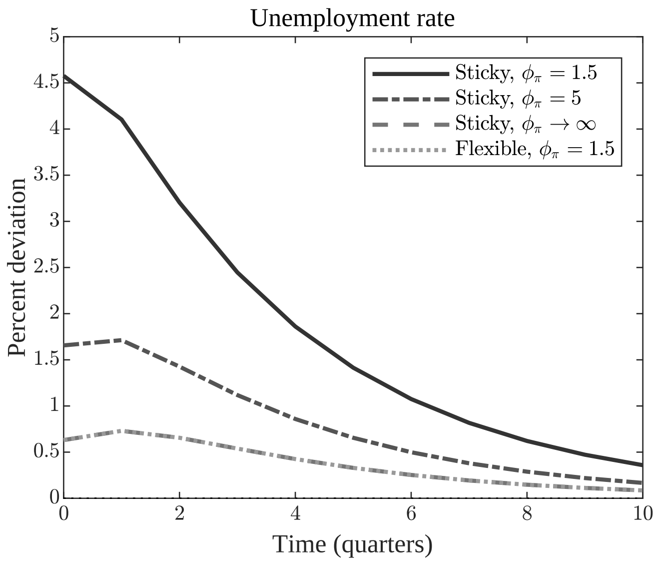
available for consumption to be significantly lower. Their pessimism about the future then induces a causal dynamic similar to the asymmetry-demand channel and exacerbates the recession caused by an uncertainty shock.

The second observation is that moving from $\phi_y = 0$ to $\phi_y = 0.2$ now *amplifies* the rise in unemployment, contrary to the comparative dynamics result for the benchmark case (with $c_t = z_t n_t$) discussed previously. We can see this in a “diff-in-diff” manner by comparing the difference between the black-solid and dark-dash-dotted lines in Figure 11 to the difference between the medium-dashed and light-dotted lines. As explained above, a central bank that is is responsive to output will limit the volatility of employment generated by productivity shocks and, as a result, can quell the rise in mean unemployment associated with an increase in technological volatility. However, the cost of doing so is greater inflation variability and, hence, more resources devoted to price adjustments. Consequently, following a volatility shock households become pessimistic about future consumption either because employment is expected to be significantly more volatile (when the central bank ignores output fluctuations) or because inflation is anticipated to be more variable (when the Taylor rule does give weight to output deviations). In either scenario, risk-averse household members expect a shortfall in aggregate demand and hence a fall in in the relative price of intermediate goods in the future, causing a drop in the value of equity today.

In summary, under the assumption that inflation variability is effectively not costly in resource terms the central bank has a “free lunch” by responding to fluctuations in output. When price adjustment costs enter the resource constraint, however, then monetary authorities face a significant tradeoff between real fluctuations that reduce mean employment, on the one hand, and variable inflation that reduces the amount of resources available for consumption for any given level of employment, on the other hand.

What about the coefficient on inflation in the Taylor Rule, ϕ_π? Figure 12 makes the point that for a sufficiently high degree of risk-aversion, a more aggressive central bank response to inflation ends up *destabilizing* unemployment following an uncertainty shock under sticky prices. Under log utility, the upper panel demonstrates, raising ϕ_π stabilizes unemployment in response to an uncertainty shock. Indeed, in the limit of approximate price stability ($\phi_\pi \to \infty$) the effect on real variables corresponds to the flex price case. When households are more risk-averse, however, with a coefficient of relative risk-aversion of $\gamma = 5$ in this instance, raising ϕ_π from 1.5 to 5 *destabilizes* unemployment conditional on an uncertainty shock. Importantly, though, these interaction effects are non-linear, as is evident from the fact that here, too, $\phi_\pi \to \infty$ again approximates the case of flexible prices.

(a) Log utility ($\gamma = 1$)



(b) Higher risk-aversion ($\gamma = 5$)

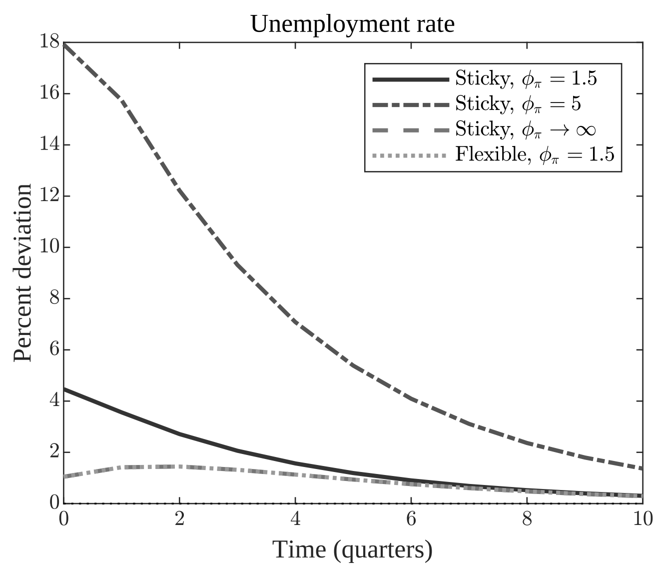


Figure 12: Varying the Taylor rule coefficient on inflation

Notes: This figure shows the impact of business cycle volatility on the mean and standard deviation of the unemployment rate (left-hand panel) and the cumulative effect of a pure uncertainty shock (right-hand panel) as a function of the worker bargaining delay value χ. Model specification: log utility, linearized NKPC, $\phi_\pi = 1.5, \phi_y = 0$.

5 Concluding Discussion

This paper contributes to the macroeconomic literatures on stochastic volatility and labor market dynamics by examining the transmission of uncertainty shocks to unemployment and inflation in a canonical model with search frictions. At the heart of our analysis is the claim that uncertainty shocks are neither akin to aggregate demand shocks nor are best described by focusing on supply-side effects only. Instead, carefully disentangling and evaluating the transmission mechanisms of uncertainty reveals the simultaneous operation of several channels, including notably: effects due to risk premia that contract potential output; and demand effects associated with precautionary savings that arise not only from prudence in preferences but also asymmetries inherent in frictional labor markets. This final section offers three concluding remarks about empirical implications of our analysis that we believe to be intriguing but quantitative evaluation of which is ongoing and outstanding work.

Our analysis is primary interested in qualitative properties of the model and, furthermore, focuses on a subset of the transmission channels that have been documented in the literature (and listed in Section 1). Several quantitative evaluations of uncertainty shocks have highlighted the difficulty estimated theoretical models have in generating large uncertainty effects that match empirical evidence. The flipside of this is that a parameterization that implies large uncertainty effects is associated with even greater, and counterfactually large, fluctuations induced by level shocks. This is also a problem troubling the canonical model studied in this paper under the benchmark calibration we use. While not the focus of the paper, our analysis of transmission mechanisms nonetheless also points towards possibilities for obtaining the sort of "asymmetric amplification" Born and Pfeifer (2014a) call for and that strengthens the propagation of *uncertainty* shocks more than that of level shocks. For example, the negative "asymmetry-demand" effects studied in Section 3.3 rest on the interaction of risk-aversion, on the one hand, and asymmetric employment dynamics due to congestion externalities in frictional labor markets, on the other hand. Empirically, labor market asymmetries of this type are well-documented.[29] It is unclear, however, whether search frictions by themselves are sufficient to quantitatively match the asymmetries observed in the data (e.g., Petrosky-Nadeau *et al.* (2018); Dupraz *et al.* (2019)). Dupraz *et al.* (2019) propose a theory in which nominal downward rigidity in wage-setting means that economic fluctuations are drops below the economy's full potential ceiling. Uncertainty shocks in such a "plucking model of business cycles" enriched with nominal rigidity would give rise to effects that parallel the "asymmetry-demand" channel documented in this paper and could be quantitatively potent. Alternatively, we flagged the presence of risk premia that arise when employment relationships are at least partially irreversible so that expectations about the volatility of future dividends affects current investment in job-creation.

[29] See, for instance, McKay and Reis (2008); Benigno *et al.* (2015); Ferraro (2018) and IMF (2019, Box 1.4).

Enriching our model with Epstein-Zin-Weil preferences and exogenous rare disasters would amplify the strengths of this risk premium channel.

Second, we argued that uncertainty shocks are distinctive because they carry both contractionary demand and supply effects. In our model, the supply-side dimension comes primarily through risk premia, but our point generalizes insofar as different transmission channels for uncertainty shocks, such as option-value effects and precautionary pricing, would likewise imply inflationary negative supply effects alongside a disinflationary demand channel. As a consequence, to the extent that uncertainty shocks have become more important in accounting for macroeconomic activity relative to "traditional" aggregate demand shocks, as anedoctal evidence would suggest they have over the past couple of years, our analysis implies that the relationship between inflation and unemployment would become less tight. That is, uncertainty shock are associated with a flatter Phillips Curve. This could have significant implications for central banks and economic policymakers more generally (e.g., Clarida (2019)). For example, in an economy buffeted around by uncertainty shocks, inflation will be a less reliable indicator for overall economic activity and a central bank strictly targeting inflation may permit large fluctuations in unemployment. At the same time, a flat Phillips curve reduces the likelihood of a surge in inflation. Finally, a related but distinct implication of our analysis concerns the "missing disinflation" puzzle discussed by Hall (2011) in his AEA Presidential Address: a large and persistent contraction of demand/rise of measures of slack during the Great Recession should imply large and persistent fall in inflation when using standard estimated Phillips curves as yard stick. Relative to that prediction, however, inflation in the US economy was remarkably stable and high.[30] We argued that uncertainty shocks are distinctive because they carry both contractionary demand and supply effects. For any given contractionary impact on unemployment, therefore, an uncertainty shock imparts less of a disinflationary impulse to the economy than a conventional aggregate demand shock (as modelled, commonly, through a discount factor shock). Measures of uncertainty, furthermore, rose sharply during the Financial Crisis. Jointly, these observations suggest that elevated uncertainty levels may have contributed to the sharp rise in unemployment in many economies while putting less disinflationary pressure than pure demand shocks would lead us to predict.[31] We leave the quantitative and empirical evaluation of this hypothesis to future work.

[30] John C. Williams' statement about the 2008-2009 experience is instructive (Williams (2010, p. 8)): "The surprise [about inflation] is that it's fallen so little, given the depth and duration of the recent downturn. Based on the experience of past severe recessions, I would have expected inflation to fall by twice as much as it has."

[31] Elevated uncertainty levels have frequently been cited in explanations of the depths and persistence of the Great Recession (e.g., Diamond (2010)). There also exist numerous papers studying the missing disinflation puzzle, including Ball and Mazumder (2011); Christiano *et al.* (2015); Coibion and Gorodnichenko (2015); Gilchrist *et al.* (2017); Bianchi and Melosi (2017) and Lindé and Trabandt (2019). We are not aware of previous work studying the intersection of the two.

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Appendix A

A.1 Proof of Proposition 1

The firm value is in this case given by

$$J(z) = \frac{(1-\omega)(xz-\zeta)}{1-\beta(1-\delta)} - \frac{\beta\omega\kappa\theta(z)}{1-\beta(1-\delta)}.$$

Suppose that $J(z)$ is (weakly) convex in the vicinity of some $z > 0$. That is

$$tJ(z_1) + (1-t)J(z_2) \geq J(z),$$

for some $z_1 > 0$ and $z_2 > 0$ and any $t \in (0,1)$ such that $z = tz_1 + (1-t)z_2$. Then by definition

$$\frac{(1-\omega)(xz-\zeta)}{1-\beta(1-\delta)} - \frac{\beta\omega\kappa(t\theta(z_1)+(1-t)\theta(z_2))}{1-\beta(1-\delta)} \geq \frac{(1-\omega)(xz-\zeta)}{1-\beta(1-\delta)} - \frac{\beta\omega\kappa\theta(z)}{1-\beta(1-\delta)},$$

or simply

$$(t\theta(z_1) + (1-t)\theta(z_2)) \leq \theta(z).$$

That is, $\theta(z)$ must be weakly concave in the vicinity of z.

The free-entry condition implies that

$$\theta(z) = \left(\frac{\psi}{\kappa}J(z)\right)^{\frac{1}{1-\alpha}},$$

which implies that $\theta(z)$ is a strictly convex function in the vicinity of z. As this is a contradiction, $J(z)$ must be strictly concave for all $z > 0$, which implies that $\theta(z)$ must be strictly convex for all $z > 0$.

The same reasoning can be applied to the case with alternating offers. □

A.2 Proof of Proposition 2

In terms of the steady state job finding rate, f, employment is given by

$$n(f) = \frac{f}{f(1-\delta)+\delta}.$$

As a consequence

$$\frac{\partial n}{\partial f} = \frac{\delta}{[f(1-\delta)+\delta]^2},$$

which is positive and monotonically decreasing. Thus $n(f)$ is increasing and strictly concave in f.

The free entry condition further implies that

$$f(z) = \psi^{\frac{1}{1-\alpha}} \kappa^{\frac{\alpha}{1-\alpha}} J(z)^{\frac{\alpha}{1-\alpha}}.$$

Thus by Proposition 1, $J(z)$ is a weakly concave function, which implies that $\alpha \leq 1/2$ is sufficient to guarantee that $f(z)$ is weakly concave, and $n(z)$ is therefore strictly concave function of z. □

A.3 Nash-Wage Channel and Policy Functions

The main text provided intuitive, analytical, and numerical reasons to think that the any uncertainty effects in the flexible prices, linear utility model are not due to option-value considerations but, instead, arise on account of Nash bargaining. An additional consideration is that local approximation methods such as perturbation would not be well-suited if the model were, in fact, to feature real options effects. For in models where option-value considerations obtain, policy functions are distinctively characterized by discontinuities reflected in regions of activity that are bounded by thresholds representing action trigger points. Local solution methods such as perturbation are not well-suited to approximating such threshold policy functions given their local non-differentiability. As per the argument of this article, in practice local solution methods yield good results for the model at hand and the policy functions obtained are continuous (even when the model is solved using a global solution method). The reason for this is precisely that there are no option-value considerations present in the model.

Figure 13 illustrates this claim by depicting the policy functions for labor market tightness (θ, upper panels) and the match value (J, bottom panels) conditional on wages being determined either according to generalized Nash bargaining (left panels) or alternative offer bargaining. Importantly, the model was solved using (global) projection methods that, in principle, could capture kinks in the decision rules. Three observations stand out. First, all policy functions are continuous, reflecting that option-value considerations are not, in fact, operative in the model. Second, as discussed in the main text, θ is convex in labor productivity and, indeed, more so under JK-wages. Finally, it is also visible that under Nash-wages, but not under alternating offers, the policy functions for both variables are *shifted down*. This is due to the workings of the Nash-wage channel described in the main text. We caution that the magnitudes are not very meaningful, as we raised the steady-state standard deviation of productivity shocks for illustrative purposes.

A.4 Robustness

This section explores three potentially important ways in which the results established so far may be subject to qualification in terms of either the transmission mechanisms explained thus far or their

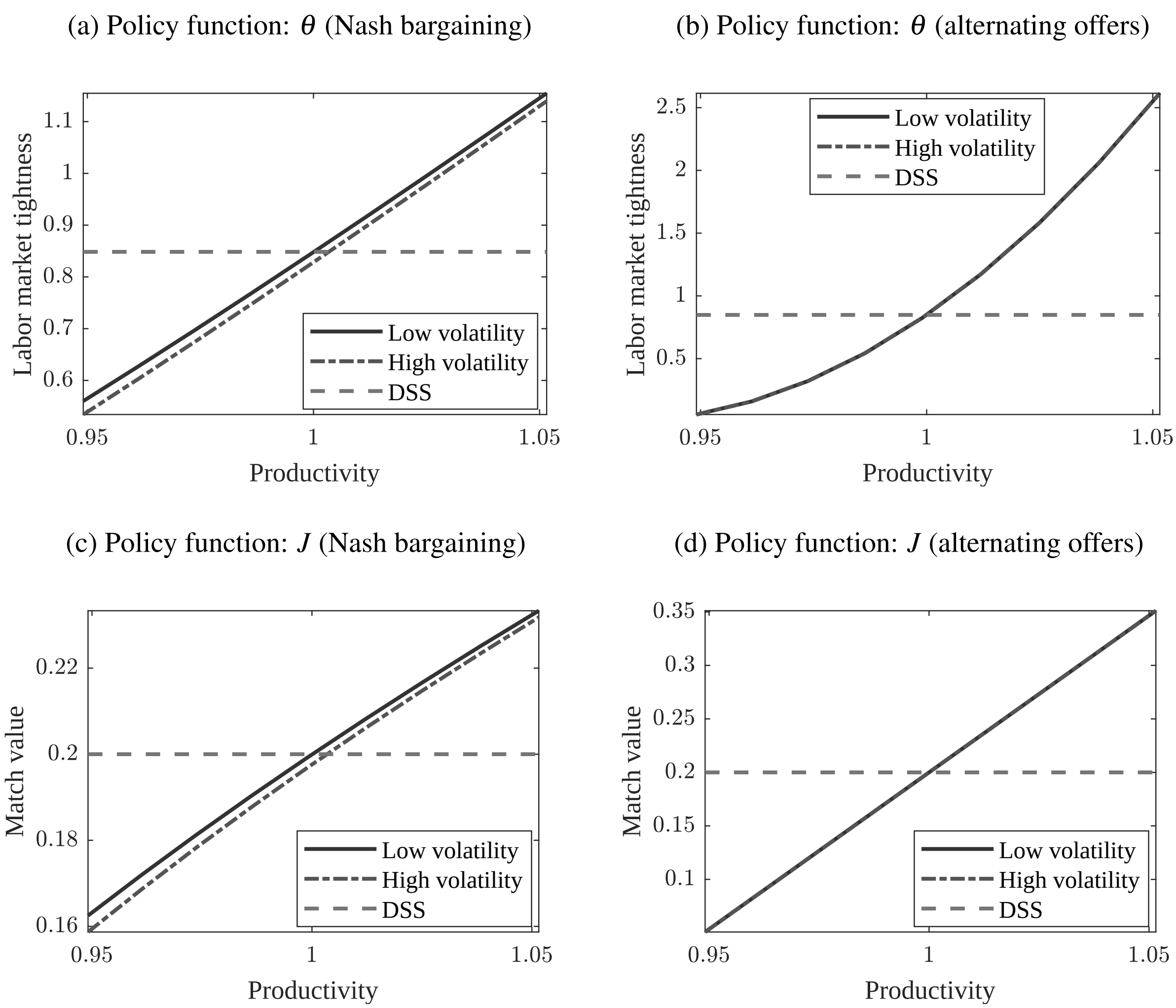


Figure 13: Policy Functions

Notes: Policy functions for labor market tightness, θ, and match value, J. Model specification: risk-neutrality, flexible prices.

quantitative significance.

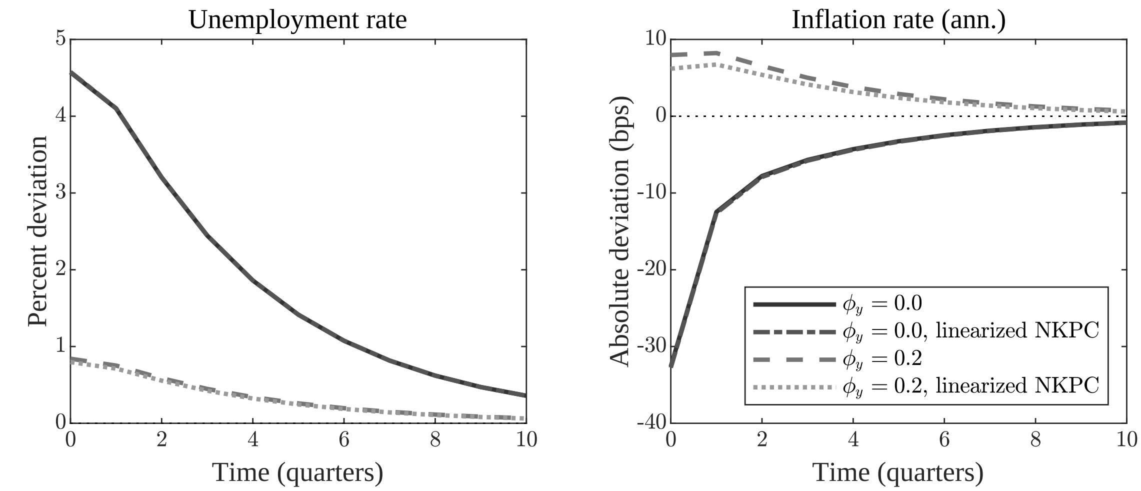
PRECAUTIONARY PRICING. Several recent contributions to the uncertainty literature highlight that precautionary price-setting behavior by firms (or unions) in the presence of nominally rigid prices (or wages) may give rise to contractionary effects of uncertainty.[32] For instance, firms situated in a Calvo (1983) environment, may bias their pricing decisions upward when uncertainy about future demand conditions increases, because their marginal revenue product exhibits convexity: it is more costly for a given firm to set too low a price relative to its competitors (more units need to be sold at a sub-optimally low price) compared to setting it too high (the higher price per unit partially compensated for fewer units sold). To assess the importance of precautionary pricing in the present setting we implement a test suggested by Fernández-Villaverde *et al.* (2015, Section VI) and compare our benchmark model with a counterfactual variant that features a linearized version of the NKPC (16); this perturbation eliminates the non-linear terms that could potentially generate an upward pricing bias.

Figure 14a shows that non-linearities in the NKPC play virtually no role when $\phi_\pi = 1.5$ and $\phi_y = 0.0$ and only a very minor role if that latter parameter is raised to 0.2. Nevertheless, consistent with the notion of precautionary pricing, to the extent that there do exist non-linearities in the NKPC, they appear to bias inflation (and markups) upward and the relative price downward, with a corresponding negative effect on job-creation. The lower panel, Figure 14b, considers the additional scenario where the central bank is highly sensitive to output deviations ($\phi_y = 1.0$). Since under this assumption inflation and, hence, the optimal response for any given retailer is more uncertain, the precautionary pricing channel takes on greater significance.

LABOR MARKET TIMING. In the theoretical model set out in Section 2, matches formed in period t become immediately productive in the same period. Here we follow the example of Blanchard and Galí (2010), Leduc and Liu (2016), and many others (see Subsection 2.3). Consistent with the overall message of the paper, which has emphasized the potentially unintended consequences of seemingly sensible assumptions, this specification of labor market timing is not innocuous: if, instead, new matches are taken to produce output only in the following period (as in, e.g., Krause and Lubik (2007) or Kilic and Wachter (2018)), then the employment asymmetries we emphasized turn out to be quantitatively weaker. We deliberately decided to stick to the former labor marker timing convention for several reasons. First, since this specification is a very common one in theoretical work, it is correspondingly important to fully appreciate its implications. Second, there exists ample empirical evidence in US data for the relationship between business cycle volatility and mean (un)employment which the asymmetry-discounting and asymmetry-demand channels are premised upon (McKay and Reis, 2008; Benigno *et al.*, 2015; Ferraro, 2018; Petrosky-Nadeau *et al.*,

[32] An incomplete list includes Fernández-Villaverde *et al.* (2015); Born and Pfeifer (2019); Ghironi and Ozhan (2019), though Oh (2019) has recently raised objections to the idea of precautionary pricing effects under Rotemberg.

(a) Scenario 1: Benchmark



(b) Scenario 2: Central Bank Highly Sensitive to Output

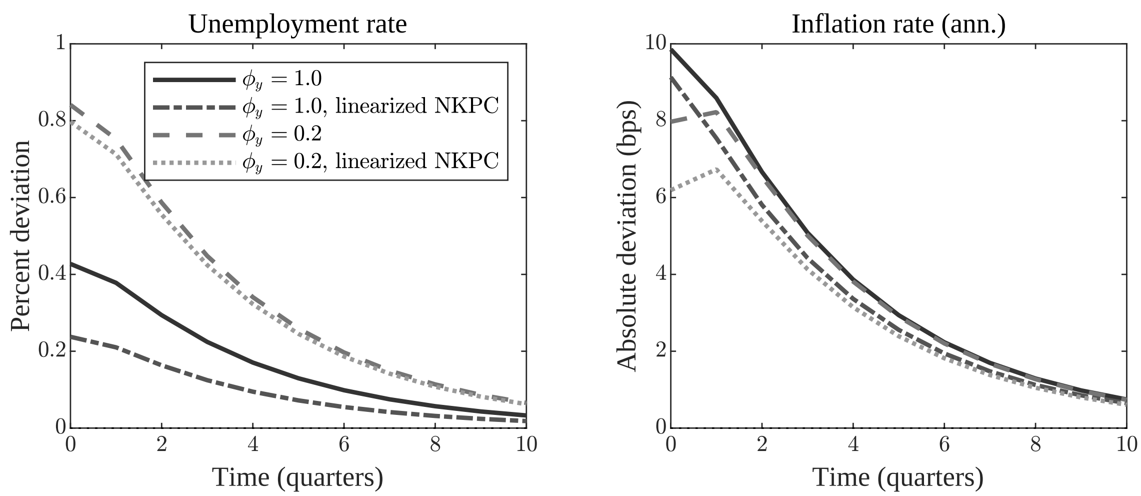


Figure 14: The Role of Precautionary Pricing

Notes: IRFs for a one-standard deviation shock to $\sigma_{z,t}$. Units are proportional deviations from stochastic steady-state (SSS). Model specification: log utility, sticky prices.

2018; Dupraz *et al.*, 2019).[33] And lastly, we believe that the mechanisms we document usefully exemplify a principle that generalizes in the following sense: a second-moment shock which is mean preserving with respect to the exogenous impulse need not be mean preserving vis-à-vis the economy as a whole if the propagation of first-moment shocks is asymmetric due to non-linearities inherent in the model equations. In this respect, we hope that the present work is instructive of approaches that may be taken to examine the complex interplay between linear exogenous shock processes and non-linear endogenous propagation.

COSTLY VACANCY CREATION. In the benchmark model we assume that vacancy posting costs are rebated to the household. If one were to suppose, instead, that these expenditures subtract from consumption in the resource constraint – that is, $c_t + \kappa v_t = z_t n_t$, supposing that price adjustment costs are "virtual" again – then this likewise gives rise to a contractionary transmission channel that operates through aggregate demand. The mechanism has its origin in vacancies v_t being convex in productivity and has recessionary effects over and above the aggregate demand effects due to employment asymmetries and/or price adjustment costs. Figure 15 shows that this channel can have quantitatively significant effects. We are not aware of any reason that would suggest this "vacancy-cost-demand" channel to be desirable.

A.5 Technical Notes

A.5.1 Definitions

Consider a dynamic and stochastic (discrete-time) system made up of just one endogenous variable, y, that is subject to the exogenous shock ε; the ideas extend to higher-dimensional systems. Write the policy function for y_t defining optimal decisions given state y_{t-1} and shock ε_t as $y_t = g(y_{t-1}, \varepsilon_t)$. To complete the notational setup, denote the past history of shocks by $\Omega_{\varepsilon,t} \equiv \{..., \varepsilon_{t-2}, \varepsilon_{t-1}\}$ and future realizations of shocks by $\Omega^f_{\varepsilon,t} \equiv \{\varepsilon_{t+1}, \varepsilon_{t+2}, ...\}$.

The deterministic steady-state (DSS) of a system refers to the fixed point of that system provided all stochastic elements are removed forever. In other words, it is the state reached in the absence of shocks and expecting no future risk. Thus, the deterministic steady-state y^{DSS} satisfies (with some misuse of notation) $g(y_t, \varepsilon_t = 0 | \Omega^f_{\varepsilon,t} = \{0, ...\}) - g(y_{t+1}, \varepsilon_{t+1} = 0 | \Omega^f_{\varepsilon,t+1} = \{0, ...\}) = 0 \quad \forall t$, and we can write it as $y^{\text{DSS}} = g(y, 0 | \Omega^f_{\varepsilon} = \{0, ...\})$.

The stochastic steady-state (SSS) of a system, on the other hand, is that point in the state-space where agents would choose to remain if there are no shocks in that period but possibly in the future.

[33] It is up for debate whether the canonical Mortensen and Pissarides (1994) model is capable of fully replicating the non-linearities characterizing labor market data (Dupraz *et al.* (2019) provide reasons to doubt this). This suggests that there is scope for further research that examines how the transmission channels we document are affected if the model is amended to include additional non-linearities. The paper by Cacciatore and Ravenna (2018) suggests that this is a promising avenue.

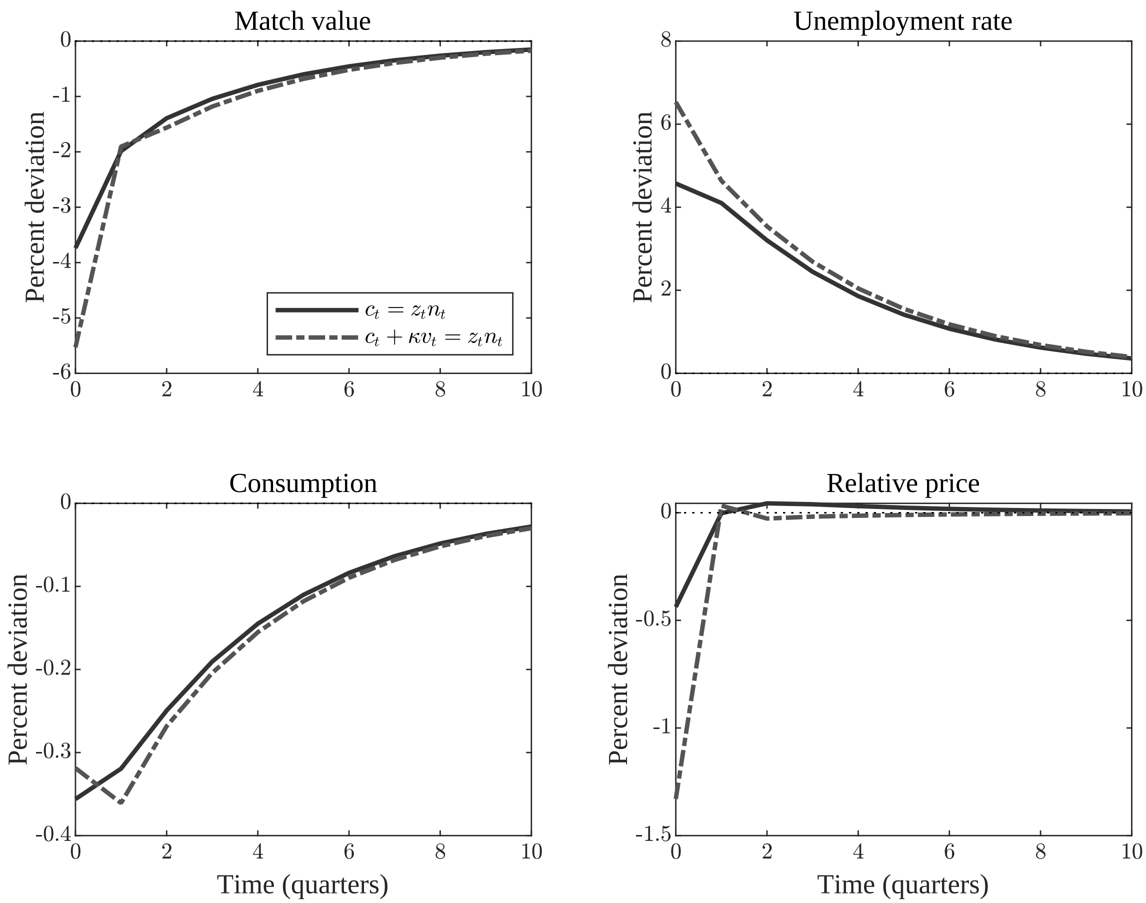


Figure 15: Implications of vacancy resource costs under sticky prices

Notes: IRFs for a one-standard deviation shock to $\sigma_{z,t}$. Units are proportional deviations from stochastic steady-state (SSS). Model specification: log utility, sticky prices, $\phi_\pi = 1.5$, $\phi_y = 0$.

That is, the stochastic steady-state satisfies $g(y_t, \varepsilon_t = 0) - g(y_{t+1}, \varepsilon_{t+1} = 0) = 0 \quad \forall t$, and, hence, $y^{\text{SSS}} = g(y, 0)$.

Finally, assuming the system satisfies stationarity and ergodicity, the ergodic mean with shocks (EMWS; also referred to as "ergodic mean" *simpliciter*) corresponds to the theoretical mean of the process when shocks evolve normally: $y^{\text{EMWS}} = E[y_t]$.

The SSS is sometimes also referred to as the "ergodic mean in the absence of shocks" (EMAS), because we can think of it also as average value in a long sample when shock realizations are zero yet agents take into account the possibility of shocks occurring. That is, $E[y_t|\varepsilon_t = 0]$. This way of thinking about the SSS is also informative about the method by which we can find the SSS. Unlike for the DSS, we cannot simply ignore randomness. Fortunately, though, we can compute the SSS using simulation-based methods – just as we would do for the EMWS. First, iterate on $y_{t+1} = g(y_t, \varepsilon_t = 0) \quad T$ times, where T is large, starting at y^{DSS}. Note that all shock realizations are zero, but each period, agents do not know that this will be the case going forward. Given the resulting sample $\{y_s\}_{s=1}^{T}$, we approximate $\hat{y}^{\text{SSS}} = y_{\text{B}+1}$, where B is the number of burn-in periods needed for the process to converge from the DSS to the SSS. By the definition of a steady-state, $y_{\text{B}+1} = y_{\text{B}+2}$ and we can equivalently say that $\hat{y}^{\text{SSS}} = \frac{1}{T-(B+1)} \sum_{l=B+1}^{T} y_l$.

A.5.2 Computation of IRFs

In general, when non-linear methods are used to solve a model, IRFs will depend on both the sequence of future shocks and the point in the state space at which the IRFs is started, i.e., the past history of shocks. Given the additional complexities, Koop *et al.* (1996) suggest the use of "Generalized Impulse Response Functions" (GIRFs). The GIRF of variable y at a time $t+l$ after a shock ε_t and conditional on the history of shocks $\Omega_{\varepsilon,t}$ is given by

$$GIRF_l(\varepsilon_t, \Omega_{\varepsilon,t}) = E_t[y_{t+l}|\varepsilon_t, \Omega_{\varepsilon,t}] - E_t[y_{t+l}|\varepsilon_t = 0, \Omega_{\varepsilon,t}].$$

This constitutes a "representative" IRFs at the ergodic mean in the sense that future shock realizations are averaged out.

The method of Fernández-Villaverde *et al.* (2011) we employ differs from this approach in two respects (Born and Pfeifer, 2014b). First, we condition on the future realizations of shocks being zero. Second, and consistent with this, we start the IRFs at the EMAS rather than the EMWs. The associated IRFs can be defined as follows:

$$\begin{aligned} IRF_l(\varepsilon_t, \Omega_{\varepsilon,t}) = [y_{t+l}|\varepsilon_t, \Omega_{\varepsilon,t} = \{...,0\}, \Omega^f_{\varepsilon,t} = \{0,...\}]... \\ -[y_{t+l}|\varepsilon_t = 0, \Omega_{\varepsilon,t} = \{...,0\}, \Omega^f_{\varepsilon,t} = \{0,...\}]. \end{aligned}$$

Note that we may drop the expectations operators, since everything is deterministic.