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Abstract

This paper studies how strategic complementarities generated by real rigidities affect the propagation of uncertainty shocks. The focus here is on two commonly featured forms of pricing complementarities that result at the firm level, in particular from i) decreasing returns to scale or the presence of firm-specific inputs (within the class of constant elasticity demand functions), ii)Kimball-type aggregator (within the class of demand functions with state-dependent elasticities). While the two mechanisms have qualitatively similar implications to first-order, their effects on the propagation mechanism of uncertainty shocks are cardinally different. In particular, firm-specific inputs strengthen the contractionary impact of uncertainty shocks by amplifying the upward pricing channel. With the Kimbal aggregator, on the contrary, firms bias

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their pricing decision downward, generating an expansionary effect of heightened uncertainty on the economic activity.

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1 Introduction

Real rigidities are mechanisms that dampen the response of prices to aggregate economic conditions. They are essential for any successful explanation of short-run macroeconomic fluctuations, in particular, inflation inertia and persistent effects of nominal shocks on output.[1]. As a result, various forms of real rigidities have become integral parts of modern state-of-the-art models of business cycle fluctuations.

Simultaneously, another strand of the recent literature studies the implications of macroeconomic uncertainty in driving business cycles.[2] Surprisingly, little attention has been devoted to exploring the implications of real rigidities for the propagation of uncertainty shocks. The current research aims to fill in this gap. Of particular interest here is how real rigidities affect the upward pricing mechanism (also labeled as precautionary pricing channel)- arguably the dominant channel among the identified mechanisms in the literature.

My focus here is on pricing complementarities that result at the firm level, in particular from decreasing returns to scale/the presence of firm-specific inputs (within the class of Dixit-Stiglitz CES demand functions (Dixit and Stiglitz (1977)) and from demand curves with state-dependent elasticities (within the class of Kimball-type demand structure (Kimball (1995)).

For the sake of simplicity but without loss in generality, I adopt the simplest possible modeling framework featuring monopolistic competitive firms and labor as the only production input. I introduce the demand structure with state-dependent elasticity into the baseline model using Dotsey and King's (2005) version of the

[1]The importance of real rigidities has been emphasized in, among others, Ball and Romer (1990), Kimball (1995), Woodford (2003, 2005), Dotsey and King (2005), Coenen et al. (2007), Smets and Wauters (2007), and Altig et al. (2011).

[2]See, among others, Basu and Bundick (2017), Born and Pfeifer (2014, 2021), Fernandez-Villaverde et al. (2011, 2015).

Kimball aggregator. Firm-specific factors are modeled assuming intermediate good firms operate with decreasing returns to scale production function. The latter is a widespread mechanism of treating production inputs (capital input, in particular) as firm-specific,[3] even though the underlying assumption that the capital stock of each firm is exogenously given is not very realistic.

The findings of the paper are as follows. The two forms of real rigidities strengthen the markup channel.[4] As for the upward pricing channel, the implications of the considered real pricing frictions are fundamentally different. In particular, firm-specific factors reinforce the upward pricing channel amplifying the contractionary impact of uncertainty shocks in general equilibrium. The Kimball aggregator, on the contrary, reverses the upward pricing effect. In this case, firms bias their pricing decision downward, generating an expansionary macroeconomic impact of heightened uncertainty. The intuition for these results goes as follows. Firm-specific factors intensify the profit function asymmetry[5] by introducing a concave relationship between the optimal reset price and the marginal cost. The precautionary pricing channel becomes stronger, resulting in a more significant impact of uncertainty shocks on economic activity. The Kimball aggregator assumes that a firm's demand elasticity is an increasing function of its relative price. The resulting profit function is strongly asymmetric, and in the face of increased uncertainty, under-pricing is an optimal behavior for firms.[6] In general equilibrium, the latter implies an expansionary effect

[3]See, e.g., Gali et al. (2001), Sbordone (2002), and Woodford (2003, chap.3).

[4]Though not often acknowledged in the relevant literature, the markup channel and the upward pricing channel are two distinct mechanisms through which aggregate uncertainty affects economic activity. The markup channel is still operative in a world where firms display no precautionary behavior (due to, e.g., flat reward function). See Basu and Bundick (2017) for a thorough discussion of the topic. More on the propagation mechanism of uncertainty (including the markup channel and the upward pricing mechanism) can be found in Born and Pfeifer (2014).

[5]Under firm-specific factors, the marginal profit function becomes more convex.

[6]The marginal profit function with Kimball-type demand structure is concave.

of heightened uncertainty.

This work is related to three strands of studies. First, this paper adds to the literature that studies the propagation of uncertainty shocks in sticky-price New Keynesian models[7] This is the first paper to consider the implications of micro, firm-level rigidities for the transmission mechanism of uncertainty shocks. Following the influential work of Basu and Bundick (2017), there is almost a unified agreement within this strand that non-competitive, sticky price models can generate empirically reasonable contractionary output responses after an uncertainty shock. I, by contrast, show that this result is not generally robust and depends crucially on the assumptions regarding the demand system. In particular, with a non-constant elasticity demand structure, uncertainty shocks are expansionary even in a model with nominal price stickiness. Within this group of studies, Oh (2019) compares the propagation of uncertainty shocks under Rotemberg (1982) and Calvo (1983) price mechanisms. He shows that contrary to the Cavlo scheme, firms subject to Rotemberg pricing, do not display upward pricing behavior as they have a flat marginal profit schedule. He also argues that the upward pricing mechanism is specific to the Calvo setup. By contrast, I show that it is not the price-setting scheme per se that gives rise to the upward pricing mechanism but the adopted demand structure. My second contribution to this strand of literature is to show that firm-specific factors amplify the effects of uncertainty shocks on the economy (both on output and prices).

This paper also contributes to the literature that studies the implications of real rigidities in the transmission mechanism of macroeconomic shocks. Among others, Kimball (1995), Rotemberg (1996), Ascari (2003), Woodford (2003), Huang and Liu

[7]Prominent examples include, among others Fernández-Villaverde et al. (2015), Born and Pfeifer (2014), Basu and Bundick (2017)

(2002, 2003), Gertler and Leahy (2007), and Altig et al. (2011) show how different types of real rigidities shape the transmission mechanism of macroeconomic shocks (dominantly monetary policy shocks). The current paper differs from these and other studies focusing on second-order uncertainty shocks. As an additional result, I find that, unlike first-order shocks, the impact of uncertainty shocks on prices is more significant with the presence of real rigidities. The latter stands in contrast to the conventional notion that strategic complementarities make the prices less responsive to variations in aggregate conditions.

The third group of studies analyzes the nonlinear implications of real rigidities. Levin et al. (2008) and Levin et al. (2007) study how different forms of real rigidities affect the welfare costs of inflation and the design of optimal monetary policy. Lindé and Trabandt (2018) and Harding et al. (2022) show that in a non-linear setup, the Kimball aggregator implies that inflation becomes much less responsive to changes in aggregate conditions in deep recessions. The latter carries important implications for fiscal spending multipliers in long-lived liquidity traps and can rationalize the observed breakdown between inflation and economic activity during the Great Recession. The current paper contributes to these studies by studying how real rigidities affect the transmission mechanism of second-order uncertainty shocks.

The rest of the paper is structured in the following way. The second section builds intuition on how real rigidities shape the upward pricing mechanism. The third section introduces the model environment used in quantitative simulations. This section also briefly discusses the procedure of computing impulse response functions to uncertainty shocks. The fourth section gives the main theoretical results concerning the role of real rigidities in the effects of uncertainty shocks. Finally, the last section summarizes and concludes the analysis.

2 The propagation of uncertainty shocks: Intuition in a static framework

The literature has outlined several channels through which elevated macroeconomic uncertainty affects the business cycle.[8] Arguably, the most important of them is the upward pricing mechanism. Monopolistic firms with precommitted nominal prices display upward pricing behavior when uncertain about future economic conditions.[9] This increase in markups leads to an output contraction.

In the current work, I study how real rigidities shape the price-setting behavior of firms when the perceived future uncertainty increases. I consider two commonly featured forms of (firm-level) rigidities. The first friction arises from firm-specific factors (assuming a conventional Dixit-Stiglitz-type demand structure). The second type of rigidity amplifies strategic complementarities via state-dependent demand elasticity in the spirit of Kimball (1995). The Kimball aggregator implies a more general demand structure and nests the Dixit-Stiglitz aggregator as its particular case. Both mechanisms have similar qualitative implications to first-order; they lower the sensitivity of prices to aggregate economic conditions. Firm-specific factors achieve this goal by introducing a concave relationship between the price and the marginal cost. The Kimball aggregator reduces the responsiveness of firms' prices to aggregate economic conditions by introducing a positive relationship between relative prices and demand elasticities.

I explore how real rigidities affect pricing decisions by using a one-period model

[8] Born and Pfeifer (2014) provides a thorough discussion on the topic.
[9] This result goes back to Kimball (1989).

of a monopolist's behavior under nominal price stickiness. The profit function (in real terms) of the firm is given by:

$$\pi(p_j) = (p_j - mc_j(p_j))y_j(p_j) \tag{1}$$

where p_j is the relative price set by the firm. mc_j and y_j denote the marginal cost and the output of the firm. For parsimony, assume that the firm faces a symmetric mean-preserving uncertainty about the reset price level. The firm solves the following expected profit maximization problem:

$$\max_{p_j} E\pi(p_j + e) \tag{2}$$

where e is a random variable with mean zero and positive variance that captures uncertainty (realized after the price is set). The baseline specification assumes a standard Dixit–Stiglitz-type demand function and a production technology that is linear in labor. One can introduce firm-specific factors assuming a decreasing return to scale production technology. The marginal cost function in the latter case depends not only on economy-wide factor markets but also on the firm's output (and, therefore, on the relative reset price). I introduce the Kimball-type demand aggregator following Dotsey and King (2005). Table 1 shows the form of the profit function (along with the optimal pricing rule) under the three specifications.

As already discussed in, among others, Born and Pfeifer (2014) and Fernandez Villaverde et al. (2015), under the conventional Dixit-Stiglitz demand structure, $p^*_{j,E} > p^*_j$.[10] This result hinges on the strict convexity of the marginal profit func-

[10] $p^*_{E,j}$ and p^*_j denote the solutions to the expected profit maximization problem and the corresponding problem without uncertainty, respectively.

Table 1. Forms of profit schedules and corresponding pricing rules

	Profit schedules
Baseline	$\pi^B = p_j^{1-\epsilon} - mcp_j^{-\epsilon}$
Firm-Specific Factors	$\pi^{DRS} = p_j^{1-\epsilon} - mcp_j^{\frac{-\epsilon}{1-\alpha}}$
Kimball Aggregator	$\pi^K = \frac{1}{1+\psi}(p_j^{-\epsilon(1+\psi)} + \psi p_j - mcp_j^{-\epsilon(1+\psi)} - \psi mc)$
	Optimal pricing rule
Baseline	$p_j^B = \frac{\epsilon}{\epsilon-1}mc$
Firm-Specific Factors	$p_j^{DRC} = (\frac{\epsilon}{\epsilon-1}mc)^{\frac{1-\alpha}{1-\alpha+\alpha\epsilon}}$
Kimball Aggregator	$p_j^K(1 - \frac{\frac{1}{\epsilon-1}\psi}{1+\psi+\psi\frac{1}{\epsilon-1}}(p_j^K)^{\epsilon(1+\psi)}) = \frac{(1+\psi)\frac{\epsilon}{\epsilon-1}}{1+\psi+\psi\frac{1}{\epsilon-1}}mc$

Notes: The table displays the profit schedules for the baseline specification and the versions with real rigidities. ϵ denotes the demand elasticity, mc is the economy-wide marginal cost. ψ measures the degree of curvature of the demand curve, $\psi < 0$. α denotes the curvature of the production function.

tion.[11] **Intuitively, the form of the profit schedule assumes that for a lower realized value of e, the firm will suffer significant profit losses if, instead of adjusting prices upward, it lowers them (or keeps them unchanged).**

Following this logic, one can also show that with a constant-elasticity demand structure, firm-specific factors strengthen the impact of uncertainty on the reset price. Figure 1 plots the marginal profit schedules for the baseline specification and the one with firm-specific factors. Firm-specific factors make the marginal profit curve more convex. Therefore, price-setting firms become more cautious and respond stronger to increased uncertainty. This result is interesting, given the fact that real rigidities are known as mechanisms reducing the responsiveness of firms' profit-maximizing prices to variations in aggregate conditions.

[11] Appendix A contains a formal discussion of the topic.

As already noted, the upward pricing behavior stems from the convex marginal profit curve. The convexity of the marginal profit function, however, is a particular implication of the adopted constant-elasticity demand structure and does not necessarily hold for more general-type demand structures. In particular, with the Kimball demand aggregator, the marginal profit curve becomes concave in the optimal price, implying a decrease in optimal price in response to uncertainty.[12] Figure 3 visualizes the underlying intuition. It plots the profit schedule along with the expected profit schedule under the Kimball aggregator. The expected profit schedule shifts to the left, implying a lower optimal price. Note that maintaining the price at the level that would be optimal in the absence of uncertainty is suboptimal too.

The following analysis explores whether intuition developed in the current section carries over to a dynamic general equilibrium framework. The ultimate goal is to quantify the role of the considered real rigidities in the propagation of uncertainty shocks in a dynamic, general equilibrium model.

3 Model Economies

In this section, I present three New Keynesian models to explore the implications of real rigidities for the propagation of uncertainty shocks. In all three variants, labor is the only input in the production technology of intermediate goods firms. I further assume that wages are flexible while prices are subject to nominal stickiness, similar to Calvo (1983). The main focus of the current paper is the upward pricing mechanism arising from an increase in future perceived uncertainty. In this respect, the adopted simplifying assumptions do not have crucial implications for the final

[12] Figure 2 shows how the marginal profit changes with respect to the relative price for the Kimball and the conventional Dixit-Stiglitz aggregator (under the baseline specification).

results. The presented model variants differ only in the source of real rigidity. The first variant-the baseline framework-assumes the Dixit-Stiglitz demand aggregator and constant returns to scale production technology. The second model variant features decreasing returns to scale production technology(with Dixit-Stiglitz aggregator) to capture factor specificity. Finally, the third model variant exhibits real rigidity due to the Kimball demand structure.

3.1 Households

An infinitely-lived representative household seeks to maximize an additively separable utility function over consumption and labor:

$$\begin{aligned} \max_{C_t,B_t,N_t} \quad & E_0 \sum_{t=0}^{\infty} \beta^t \xi_t \left(lnC_t - \frac{N_t^{\phi+1}}{1+\phi} \right) \\ \text{s.t.} \quad & P_t C_t + B_t = W_t N_t + B_{t-1} R_{t-1} + \Omega_t \end{aligned} \tag{3}$$

C_t is the aggregate consumption index, N_t is the labor supply and ξ_t is the preference shock. R_t is the gross nominal interest rate and W_t is the nominal wage. Ω_t and B_t denote the dividends from holding shares in the equity of firms and purchases of one-period bonds (which must be zero in equilibrium), respectively. β is the time discount factor, and ϕ denotes the inverse of the Frisch elasticity of labor supply.

The optimality conditions imply that the household supplies labor up to the point where the marginal cost of working equals the real wage:

$$\frac{N_t^{\phi}}{\lambda_t} = w_t \tag{4}$$

λ_t is the marginal utility of consumption and w_t denotes real wage. On the other hand, the first order condition for consumption is:

$$E_t[\frac{\xi_{t+1}}{\xi_t}\frac{\lambda_{t+1}}{\lambda_t}\frac{R_t}{\Pi_{t+1}}] = 1 \tag{5}$$

3.2 Intermediate Good Firms

3.2.1 Price-Setting Scheme

The intermediate good firms set prices as in Calvo (1983). In every period, each firm faces a constant probability, $1 - \theta$, of being able to adjust its nominal price. The ability to adjust prices is independent across the firms and time. The dynamic problem of a re-optimizing firm (given the demand for its output) is written as:

$$\max_{P_t(j)^{op}} \quad \sum_{l=0}^{\infty}(\theta)^l E_t Q_{t,t+l}\left((P_t(j)^{op} - MC_{t+l}(j))Y_{t+l}(j)\right) \tag{6}$$

where $Q_{t,t+l} = \beta^l \frac{U_{c,t}}{U_{c,t+l}}$ is the stochastic discount factor and MC_t denotes the real marginal cost function of firm j.

3.2.2 Production technology

In the baseline framework, I assume that intermediate good firms possess an identical constant return to scale production function:

$$Y_t(j) = a_t N_t(j) \tag{7}$$

$Y_t(j)$ denotes output and $N_t(j)$ is the labor demand of firm j. a_t is a common productivity factor.

In the second model-variant, factor attachment is introduced via decreasing returns to scale production technology:

$$Y_t(j) = a_t(N_t(j))^{\alpha}, \qquad \alpha \in (0,1) \tag{8}$$

As for the third variant with the Kimball demand structure, the production technology is the same as in the baseline case.

3.3 Final Good Producers

In the baseline framework and in the model version with firm-specific factors, the representative firm combines intermediate goods $Y_t(j)$ to produce the final good Y_t by using a Dixit-Stiglitz-type CES bundling technology:

$$\int_0^1 (\frac{Y_t(j)}{Y_t})^{\frac{\epsilon-1}{\epsilon}} dj = 1 \tag{9}$$

Here ϵ is the elasticity of substitution between different varieties. The representative firm takes the aggregate price level, P_t, and the price of intermediate goods, $P_t(j)$, as given. It chooses intermediate good quantities, $Y_t(j)$ to maximize profits. The usual demand schedule is given by:

$$Y_t(j) = (\frac{P_t(j)}{P_t})^{-\epsilon} Y_t \tag{10}$$

At the same time, the zero profit condition of the representative firm yields the following relation for the aggregate price level, $P_t = \left(\int_0^1 P_t(j)^{1-\epsilon} dj\right)^{\frac{1}{1-\epsilon}}$.

The third model version features a Kimball-type demand aggregator similar to Dotsey and King (2005):

$$\int_0^1 \left(\frac{\frac{\epsilon}{\epsilon-1}}{1+\psi}((1+\psi)\frac{Y_t(j)}{Y_t} - \psi)^{\frac{\epsilon}{\epsilon-1}} + 1 - \frac{\frac{\epsilon}{\epsilon-1}}{1+\psi} \right) dj = 1 \tag{11}$$

Here $\psi \leq 0$ determines the degree of curvature of the intermediate firm's demand curve. The first-order conditions of the profit maximization problem are given by:

$$\frac{Y_t(j)}{Y_t} = \frac{1}{1+\psi}((\frac{P_t(j)}{P_t}\frac{1}{\upsilon_t})^{-\epsilon(1+\psi)} + \psi) \tag{12}$$

$$P_t\upsilon_t = (\int_0^1 P_t(j)\frac{1+\psi\frac{\epsilon}{\epsilon-1}}{1-\frac{\epsilon}{\epsilon-1}}dj)^{\frac{1-\frac{\epsilon}{\epsilon-1}}{1+\psi\frac{\epsilon}{\epsilon-1}}} \tag{13}$$

$$\upsilon_t = 1 + \psi + \psi\int_0^1 \frac{P_t(j)}{P_t}dj \tag{14}$$

Notice that for $\psi = 0$, (12) and (13) are the standard Dixit-Stiglitz demand equation and aggregate price index, respectively.

3.3.1 Equilibrium and Market clearing

One can easily show that the aggregate resource constraint in the baseline economy takes the following form:

$$C_t = Y_t = \frac{a_t N_t}{D_t} \tag{15}$$

where $N_t = \int_0^1 N_t(j)dj$ is the aggregate labor and D_t measures price dispersion across firms:

$$D_t = \int_0^1 (\frac{P_{t,j}}{P_t})^{-\epsilon}dj = (1-\theta)(\frac{P_t^*}{P_t})^{-\epsilon} + \theta\Pi_t^{\epsilon}D_{t-1} \tag{16}$$

The relative price dispersion in the model with the Kimball aggregator is more involved and is given by:

$$D_t = \frac{1}{1+\psi}D_{2,t}^{\frac{\epsilon(1+\psi)}{1-\epsilon(1+\psi)}}D_{1,t} + \frac{\psi}{1+\psi} \tag{17}$$

$$\frac{1}{1+\psi}D_{2,t}^{\frac{1}{1-\epsilon(1+\psi)}} + \frac{\psi}{1+\psi}D_{3,t} = 1 \tag{18}$$

$$D_{1,t} = (1-\theta)(\frac{P_t^*}{P_t})^{-\epsilon(1+\psi)} - \theta\Pi_t^{\epsilon(1+\psi)}D_{1,t-1} \tag{19}$$

$$D_{2,t} = (1-\theta)(\frac{P_t^*}{P_t})^{1-\epsilon(1+\psi)} - \theta\Pi_t^{\epsilon(1+\psi)-1}D_{2,t-1} \tag{20}$$

$$D_{3,t} = (1-\theta)\frac{P_t^*}{P_t} + \theta\Pi_t^{-1}D_{3,t-1} \tag{21}$$

As for the version with firm-specific inputs we have:

$$C_t = Y_t = a_t(\frac{N_t}{D_t})^{1-\alpha} \tag{22}$$

where

$$D_t = (1-\theta)(\frac{P_t^*}{P_t})^{-\frac{\epsilon}{1-\alpha}} + \theta\Pi_t^{\frac{\epsilon}{1-\alpha}}D_{t-1} \tag{23}$$

3.4 Closing the model

I close the model by describing the behavior of the nominal interest rate and the stochastic processes driving the economy.

3.4.1 Monetary policy

The Central Bank follows a simple interest rate rule:

$$\frac{R_t}{R} = \left(\left[\frac{\Pi_t}{\Pi}\right]^{\mu_\Pi}\left[\frac{Y_t}{Y}\right]^{\mu_Y}\right)m_t \tag{24}$$

μ_π and μ_Y control the responses to inflation and output. The letters without a time subscript mark corresponding steady-state values. Finally, m_t is a monetary policy shock.

3.4.2 Shocks

For parsimony, the model features only three level shocks i) a "supply-side" productivity shock, a_t; ii) a "demand-side" preference shock, ξ_t; and iii) a monetary policy shock, m_t. Associated with each of these shocks will be three corresponding second-order uncertainty shocks, for a total of six shocks:

$$\ln x_t = \rho_x \ln x_{t-1} + e^{\sigma_t^x} \varepsilon_{x,t} \tag{25}$$

$$\sigma_t^x = \rho_{\sigma^x} \sigma_{t-1}^x + \varepsilon_{\sigma^x,t} \tag{26}$$

where $x = a, \xi, m$.

3.5 Calibration and Solution

I follow the existing literature in calibrating the parameters of the model. The three model versions are parameterized to a quarterly frequency. The price stickiness parameter, θ, and the time discount factor, β are set to 0.66 and 0.99, respectively.[13]. The parameter of demand elasticity, ϵ is set to 11 which implies that the steady-state price markup is 10 percent. I set the inverse of the Frisch elasticity of labor supply, $\phi = 2$. I choose a conventional value for the curvature parameter of the production function, $\alpha = 0.3$. Regarding the Taylor rule parameters, the standard parametrization is $\mu_\Pi = 1.5$ and $\mu_Y = 0.125$.[14] Next, I set the steady-state gross inflation rate to 1. To make the two versions of the models with real rigidities equivalent to the first order, I calibrate the Kimball parameter ψ at a value such

[13]The average duration of a price contract is about 3 quarters, consistent with Nakamura and Steinsson (2008)

[14]These are in line with Gali (2015).

that linear Philips curves in the two models have the same slope:[15]

$$\frac{(1-\theta)(1-\beta\theta)}{\theta}\frac{1-\alpha}{1-\alpha+\alpha\epsilon} = \frac{(1-\theta)(1-\beta\theta)}{\theta}\frac{1}{1-\frac{\epsilon}{\epsilon-1}\psi}$$

Given the above logic, I set $\psi = -4.3$

Table 1 summarizes the model calibration.

I solve the model by third-order approximation to account for the role of uncertainty shocks. As in Basu and Bundik (2017), the simulations are centered around the stochastic fixed point of the model. The latter is the rest point of the approximated decision rules where the current shocks are zero, but future shocks have nonzero variance. The stochastic fixed point is computed in the following way: starting from the deterministic steady-state, the model is simulated for several periods setting the variance of all current-period shocks to zero. To compute impulse responses, I first simulate the model without any shock realization given the stochastic fixed point of the model. This set of samples are the control simulations. Next, I implement the same simulations adding an appropriate uncertainty impulse. Finally, I subtract control simulations from the series with impulse. An alternative procedure commonly used in literature is based on the generalized impulse response of Koop et al. (1996). Instead of being centered around the stochastic fixed point, these impulse responses are computed in deviations from the ergodic mean of the variables. When doing simulations, I find that both procedures deliver similar results.

[15]The left-hand side of the expression represents the model with firm-specific factors and the right-hand side denotes the Phillips Curve slope in the economy with Kimball aggregator.

4 Quantitative Results

This section explores the quantitative implications of real rigidities for the propagation of uncertainty shocks. I start the section by simulating impulse response functions for the three model economies. I also present further analysis on the importance of real rigidities for the markup channel.

4.1 Baseline results

Figures 4-6 plot the impulse responses of the selected variables to a 1 standard deviation increase in uncertainty shocks. Figure 4 plots the response of the economy under baseline calibration. An increase in aggregate uncertainty leads to a drop in output and an increase in inflation. The overall impact is driven by the precautionary pricing behavior of the firms. As already discussed in Section 2, with the Dixit-Stiglitz demand aggregator, the profit function is asymmetric such that it is more costly for the firm to set too low a price rather than setting it too high. As a result, firms demonstrate upward pricing bias. This endogenous increase in price markups is contractionary in a demand-driven economy like ours.

Turning to the second model economy with firm-specific factors (Figure 5), we observe a qualitatively similar behavior of the economy responding to elevated uncertainty. One can, however, notice that under firm-specific inputs, the impact of uncertainty on the economy is much stronger. The response of output and inflation is more than four times stronger in the economy with firm-specific factors compared to the baseline case under productivity uncertainty shocks. The greater responsiveness of output to an uncertainty shock is natural to expect, having the pricing complementarity at play. However, we also observe that inflation becomes more responsive to heightened uncertainty with firm-specific factors. The latter stands in contrast to the conventional notion that strategic complementarities make the prices less responsive to variations in aggregate conditions.

Finally, Figure 6 shows that, unlike the Dixit-Stiglitz demand structure, the model with the Kimball specification generates expansionary effects of elevated uncertainty shocks. The figure shows that firms demonstrate downward pricing bias; they cut markups responding to an increase in perceived uncertainty. The latter implies a drop in the inflation rate and a rise in output. These results negate the conventional notion that non-competitive, sticky price models can generate contractionary effects following an increase in macroeconomic uncertainty. In addition, I conclude that the upward pricing mechanism is not specific to the price-setting scheme.

4.2 Further Results: Real rigidities and the markup channel

The preceding analysis has studied the implications of real rigidities for the upward pricing channel. The second mechanism through which the effects of uncertainty propagate to the economy is the markup channel. This section looks at the role of real rigidities in shaping the markup channel. To switch off the precautionary pricing mechanism and consider only the resulting markup channel, I approximate to the first order only the pricing block of the model while keeping the rest of the economy (essentially the demand side) at the third order.[16] Recall that the baseline calibrations ensure that the pricing relations in the two versions of the models with real rigidities are isomorphic to first order. Therefore, with linear pricing relations, these models deliver similar quantitative results. Given the latter, Figure 7 plots only two sets of impulse response functions: for the baseline economy

[16] This is a commonly featured exercise in the literature. See, e.g., Fernández-Villaverde et al. (2015).

and the economies with real rigidities. Not surprisingly, without the upward pricing channel, the impact of uncertainty shocks on the economy is rather limited.[17] Moreover, in the baseline economy with a linear Phillips curve, uncertainty shocks are stagnationary-they imply positive conditional covariance between the prices and output. The contractionary effects of uncertainty are due to the markup channel still operative in the model due to nominal price stickiness. Turning to the case of real rigidities, we observe qualitatively similar responses of the selected variables to uncertainty shocks. A few observations are, however, worth stressing. First, in the models with real rigidities, the impact of an uncertainty shock on output is stronger than in the baseline case. This is not surprising, given the fact that real rigidities at first-order approximation effectively imply higher nominal price sluggishness, which amplifies the markup channel. Second, with linear pricing relations, the Kimball aggregator assumes contractionary effects of uncertainty shocks. This result again assures us that the expansionary effects of uncertainty shocks observed in the fully nonlinear version of the model with the Kimball aggregator are solely driven by the precautionary pricing behavior of the firms.

5 Conclusions

This current paper studies how real rigidities affect the transmission mechanism of uncertainty shocks. I consider two forms of real rigidities: non-constant demand elasticities and upward-sloping marginal cost (firm-specific factors). I first consider the issue in a simple static model. I show that while firm-specific factors amplify the upward pricing channel, the Kimball aggregator reverses the upward pricing effect

[17]The contractionary effect of uncertainty on output in the fully non-linear model is mainly driven by the upward pricing mechanism.

making the firms bias their pricing decision downward. In a dynamic model, the latter assumes an expansionary impact of uncertainty shocks. Interestingly, contrary to the prevailing knowledge, uncertainty shocks imply expansionary output responses even in the presence of nominal rigidities. In the last part of the analysis, I ask how real frictions affect the propagation of uncertainty shocks without mechanisms generating the upward pricing channel. As expected, both frictions amplify the contractionary effects of uncertainty shocks.

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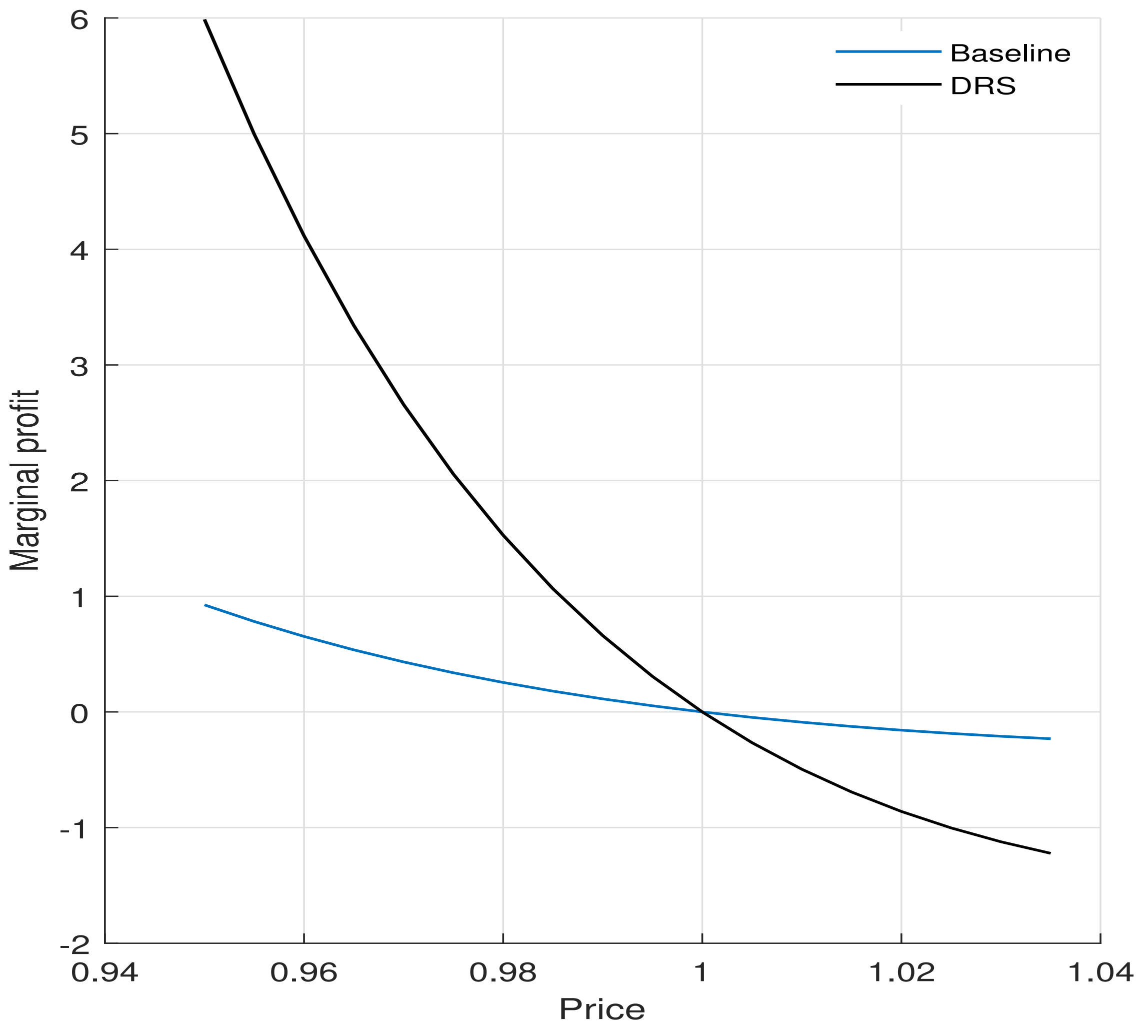
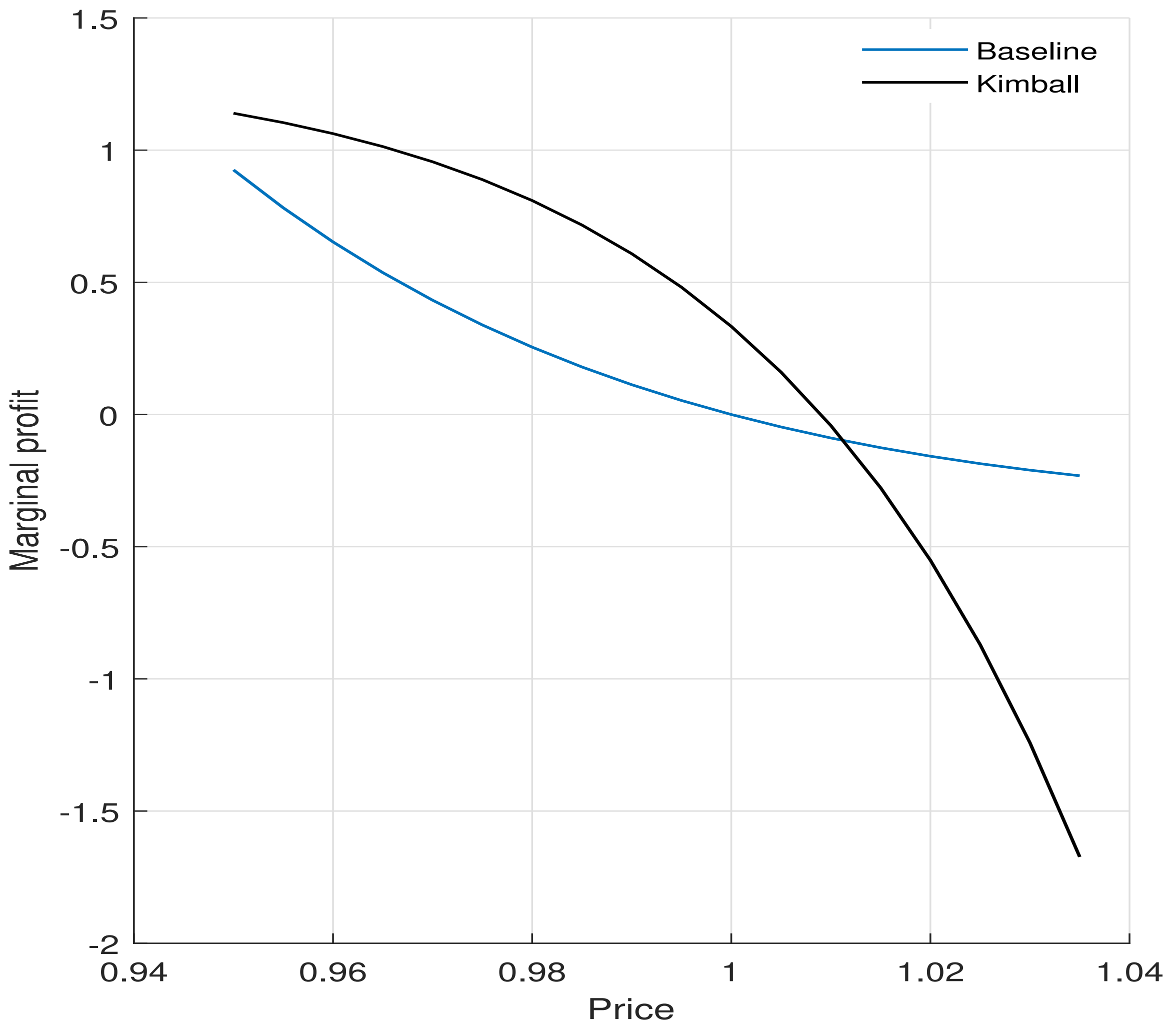
Figure 1. Marginal profit function: Baseline versus firm-specific factors



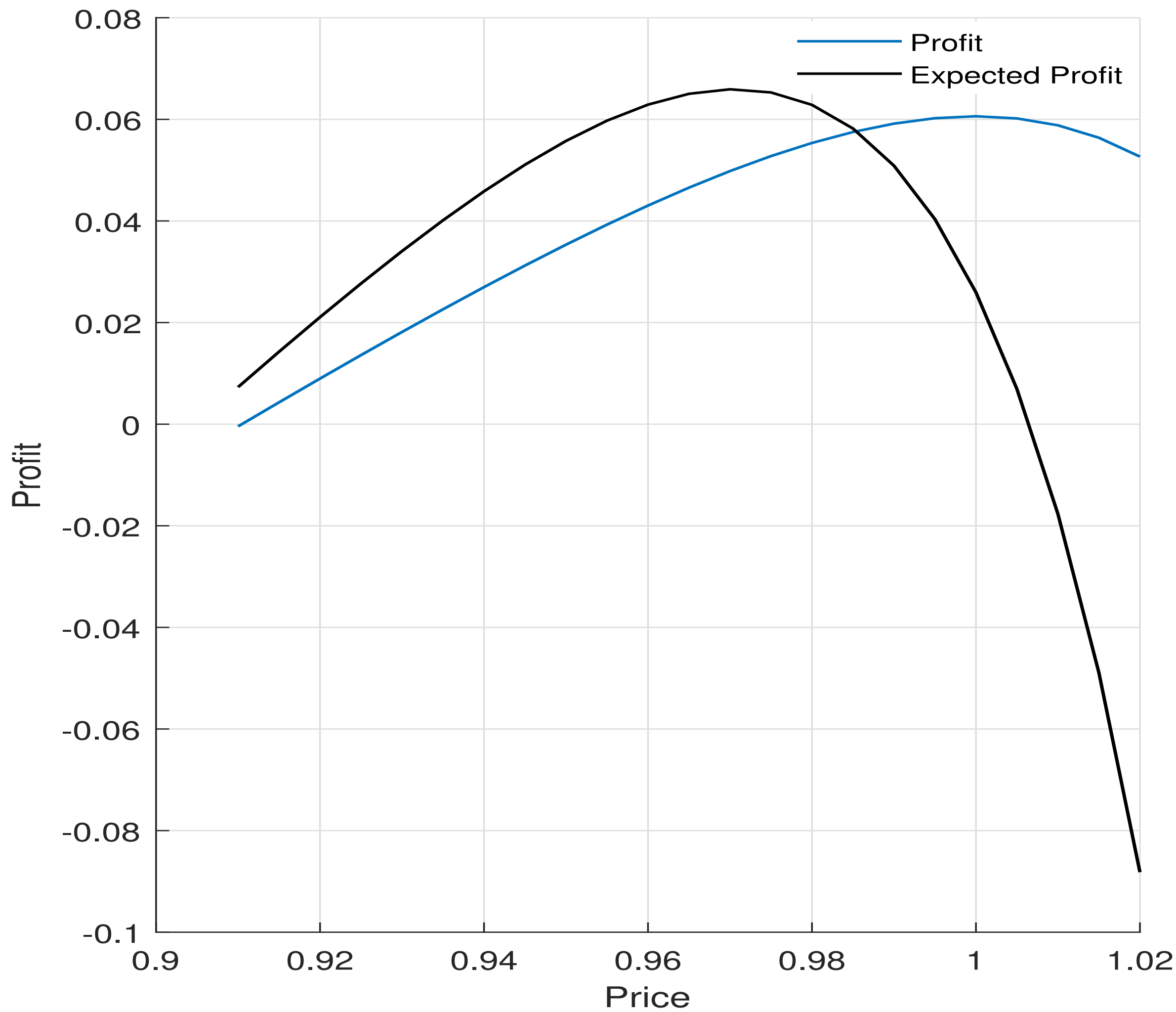
Notes: The blue line plots the marginal profit schedule for the baseline specification. The black line shows the marginal profit schedule for the specification with decreasing return to scale (firm-specific factors) production technology. In calculations, I fix $\epsilon = 11$ and $\alpha = 0.3$.

Figure 1. Marginal profit function: Baseline versus Kimball



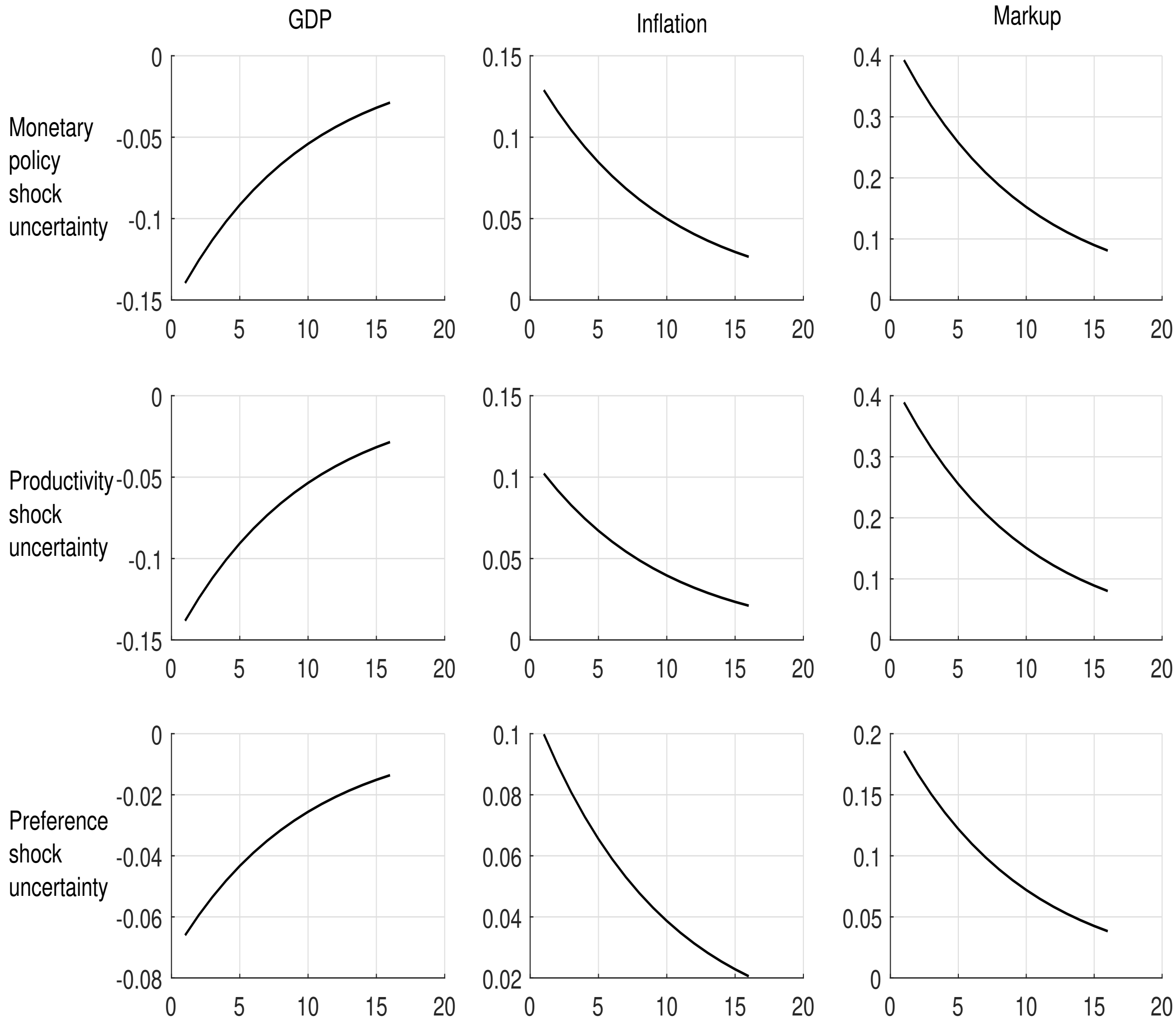
Notes: Notes: The blue line plots the marginal profit schedule for the baseline specification. The black line shows the marginal profit schedule for the specification with the Kimball aggregator. I set $\epsilon = 11$ and $\psi = -4$.

Figure 3. Profit versus expected profit schedules: Kimball aggregator



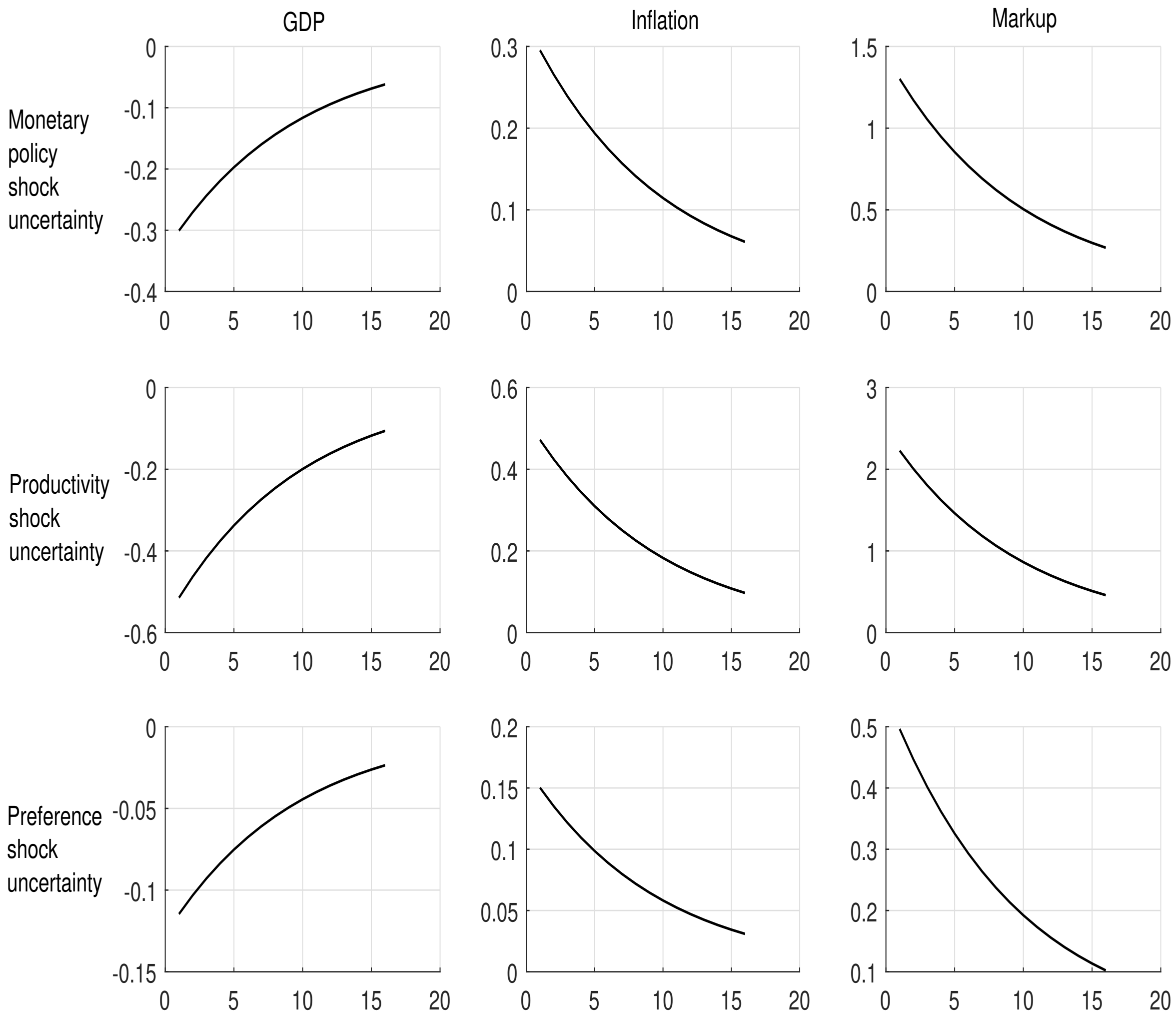
Notes: The blue and the black lines plot the profit and expected profit schedules, respectively. e is either -0.05 or 0.05 with probability $\frac{1}{2}$. $\epsilon = 11$, $\psi = -4$

Figure 4. The impact of uncertainty shocks: Baseline specification



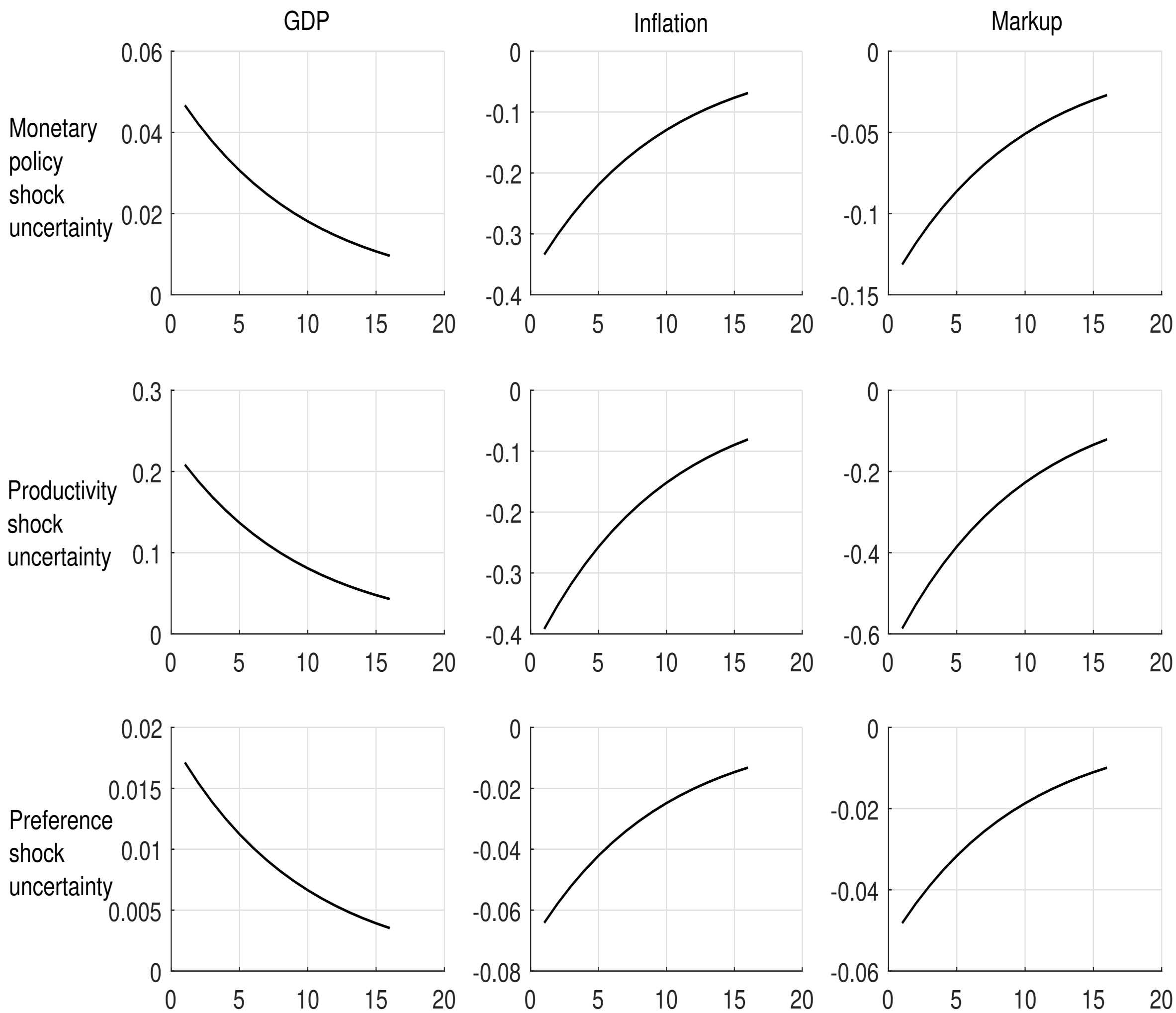
Notes: figure plots the responses of the selected variables to the three uncertainty shocks under the baseline specification. The magnitude of the shocks is the same: one standard deviation. The entries are in percentage terms. Inflation is in annualized percentage points.

Figure 5. The impact of uncertainty shocks: Firm-specific factors



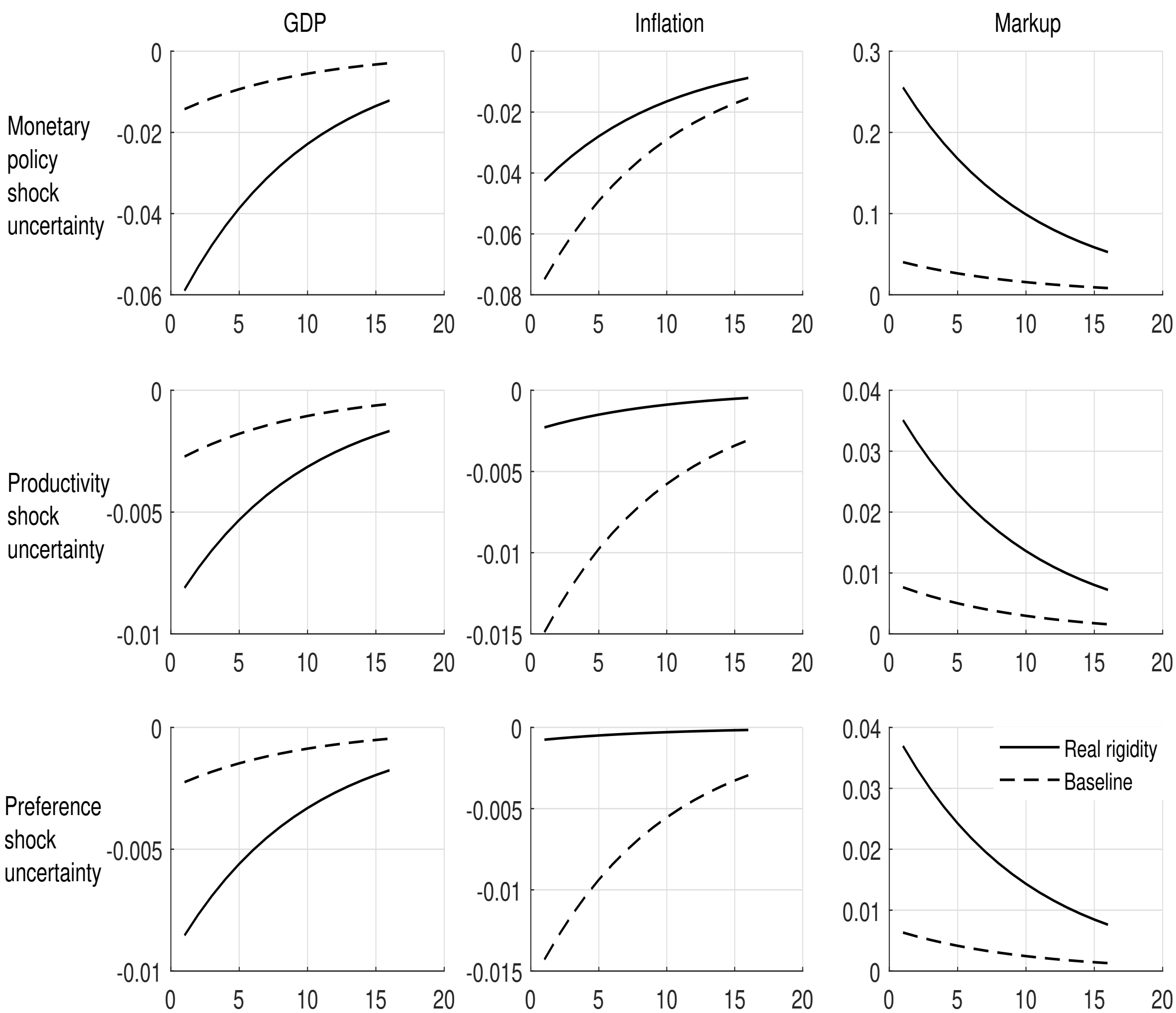
Notes: This figure is similar to Figure 4, but plots the responses in the economy with firm-specific factors.

Figure 6. The impact of uncertainty shocks: Kimball aggregator



Notes: This figure is similar to Figure 4, but plots the responses in the economy with the Kimball aggregator.

Figure 7. The impact of uncertainty shocks with flat profit schedules: Baseline versus real rigidities



Notes: The figure plots the response functions in economies with linear (linearized) pricing relations. The dashed line corresponds to the baseline economy, and the solid line shows the impulse response functions in an economy with real rigidities.

Table 1. Baseline calibration

Parameter	Description	Value
β	Time discount factor	0.99
ϕ	Inverse elasticity of labor supply	2
ϵ	Demand elasticity	11
ψ	Curvature of demand function	-4.3
θ	Price stickiness	0.66
α	Measure of decreasing returns	0.3
μ_π	Response to inflation	1.5
μ_Y	Response to output	0.125
Π	Inflation target	1.0
ρ_a	Productivity persistence	0.9
ρ_ξ	Preference persistence	0.5
ρ_m	Policy shock persistence	0.5
ρ_{σ^x}	Uncertainty shock persistence	0.9
σ_x	Level shock standard deviation	0.01
η_{σ^x}	Uncertainty shock standard deviation	1

Note: This table reports the values of parameters in the baseline calibration.

$x = a, \xi, m$

Appendix A: Price setting behavior under uncertainty

Following Kimball (1990), denote μ the "equivalent precautionary premium", such that

$$\frac{\partial E\pi(p^*_{j,E}, e)}{\partial p_j} = \frac{\partial \pi(p^*_{j,E} + \mu)}{\partial p_j} = 0 \tag{A.1}$$

where $p^*_{j,E}$ solves the expected profit maximization problem (2), and $p^*_j = p^*_{j,E} + \mu$ is the solution of the corresponding problem without uncertainty. Consider a first order Taylor expansion of $\frac{\partial \pi(p^*_{j,E}+\mu)}{\partial p_j}$ and a second-order Taylor expansion of $\frac{\partial E\pi(p^*_{j,E},e)}{\partial p_j}$ around the stationary point $p^*_{j,E}$:

$$\frac{\partial \pi(p^*_{j,E} + \mu)}{\partial p_j} \approx \frac{\partial \pi(p^*_{j,E})}{\partial p_j} + \frac{\partial^2 \pi(p^*_{j,E})}{\partial p_j^2}\mu \tag{A.2}$$

$$\frac{\partial E\pi(p^*_{j,E}, e)}{\partial p_j} \approx \frac{\partial \pi(p^*_{j,E})}{\partial p_j} + \frac{1}{2}\frac{\partial^3 \pi(p^*_{j,E})}{\partial p_j^3}\sigma^2 \tag{A.3}$$

where σ^2 is the variance of e. Combining A.2 and A.3, one gets that for a small mean-zero uncertainty e:

$$\mu = \frac{\frac{1}{2}\frac{\partial^3 \pi(p_j)}{\partial p_j^3}}{\frac{\partial^2 \pi(p_j)}{\partial p_j^2}}\sigma^2 \tag{A.4}$$

A4 makes it clear that whether $\mu \lesseqgtr 0$ or equivalently $p^*_{j,E} \lesseqgtr p^*_j$ depends on the sign of $\frac{\partial^3 \pi(p_j)}{\partial p_j^3}$.[18] In particular, with a strictly convex marginal profit curve-which is the case under the conventional Dixit-Stiglitz demand structure-$\frac{\partial^3 \pi(p_j)}{\partial p_j^3} > 0$ and $\mu < 0$, i.e., $p^*_{j,E} > p^*_j$. The firm raises its price responding to an increase in future uncertainty.

It can be shown that firm-specific factors strengthen the "precautionary behavior" of the firm, making it respond stronger to elevated uncertainty. Intuitively,

[18]It is straightforward to show that for both Kimball and Dixit-Stiglitz aggregators, $\frac{\partial^2 \pi(p_j)}{\partial p_j^2} < 0$.

firm-specific factors make the marginal profit function "more convex", i.e.:

$$\mu^{DRS} = \frac{\frac{1}{2}\frac{\partial^3 \pi^{DRS}(p_j)}{\partial p_j^3}}{\frac{\partial^2 \pi^{DRS}(p_j)}{\partial p_j^2}}\sigma^2 < \mu^B = \frac{\frac{1}{2}\frac{\partial^3 \pi^{B}(p_j)}{\partial p_j^3}}{\frac{\partial^2 \pi^{B}(p_j)}{\partial p_j^2}}\sigma^2 \tag{A.5}$$

Finally, consider the price-setting problem under the Kimball aggregator. We have:

$$\frac{\partial^3 \pi^K(p_j)}{\partial p_j^3} = \epsilon(\epsilon(\psi+1)+1)(\epsilon(\psi+1)+2)(mc-1)p_j^{-\epsilon(\psi+1)-3} \tag{A.6}$$

For conventional parameterizations, the marginal profit function is strictly concave, $\frac{\partial^3 \pi^K(p_j)}{\partial p_j^3} < 0$. The latter implies that $\mu^K > 0$ and $p_E^* < p^*$. Under the Kimball demand system, the firm displays "imprudence" by decreasing the price in the event of increased future uncertainty.