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- We propose a macroeconomic model with a nonlinear Phillips curve that has a flat slope when inflationary pressures are subdued and steepens when inflationary pressures are elevated.
- The nonlinear Phillips curve in our model arises due to a quasi-kinked demand schedule for goods produced by firms.
- Our model can jointly account for the modest decline in inflation during the Great Recession and the surge in inflation during the post-COVID period.
- Because our model implies a stronger transmission of shocks when inflation is high, it generates conditional heteroskedasticity in inflation and inflation risk.
- Hence, our model can generate more sizeable inflation surges due to cost-push and demand shocks than a standard linearized model.
- Finally, our model implies that the central bank faces a more severe trade-off between inflation and output stabilization when inflation is elevated.

Understanding Post-COVID Inflation Dynamics*

Martín Harding[†] Jesper Lindé[‡] Mathias Trabandt[§]

May 9, 2023

Abstract

We propose a macroeconomic model with a nonlinear Phillips curve that has a flat slope when inflationary pressures are subdued and steepens when inflationary pressures are elevated. The nonlinear Phillips curve in our model arises due to a quasi-kinked demand schedule for goods produced by firms. Our model can jointly account for

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the modest decline in inflation during the Great Recession and the surge in inflation during the post-COVID period. Because our model implies a stronger transmission of shocks when inflation is high, it generates conditional heteroskedasticity in inflation and inflation risk. Hence, our model can generate more sizeable inflation surges due to cost-push and demand shocks than a standard linearized model. Finally, our model implies that the central bank faces a more severe trade-off between inflation and output stabilization when inflation is elevated.

JEL Classification: E30, E31, E32, E37, E44, E52

Keywords: Inflation dynamics, inflation risk, monetary policy, linearized model, nonlinear model, real rigidities.

1 Introduction

After more than two decades of low and stable inflation in advanced economies, inflation rose sharply following the COVID-19 pandemic. In light of the substantial evidence of flat slope of the Phillips curve, the recent surge in inflation has caught many macroeconomists off guard. Hence, an intense debate has unfolded about how to explain the increase in inflation.¹ Has the Phillips curve steepened or are large exogenous demand and supply factors key to understand why inflation has risen so much? Our paper attempts to make a contribution to this debate.

Specifically, we propose a macroeconomic model which implies a nonlinear Phillips curve. The Phillips curve in our model is flat when inflationary pressures are subdued and steepens as inflationary pressures rise. The key feature of our model underpinning this nonlinear relationship stems from a quasi-kinked demand schedule for goods produced by firms. The

¹ See e.g. Federal Reserve Chair J. Powell speech at the 2021 Jackson Hole conference as well as the debate between L. Summers and P. Krugman that took place since early 2021. See also Gopinath (2022).

flat part of the Phillips curve was used by Harding, Lindé and Trabandt (2022) to resolve the missing deflation puzzle during the Great Recession. In this paper, we argue that the same model is successful explaining post-COVID inflation dynamics.

Our explanation rests on the steeper portion of the Phillips curve, which implies that all shocks in the model transmit stronger to inflation when inflation is surging. For demand and technology shocks, the relationship between the initial inflation level and how strongly shocks propagate to inflation is precise and increases monotonically when we vary these shocks according to their estimated standard deviation. However, cost-push shocks propagate even stronger to inflation than demand and technology shocks when inflation is high and rising above its steady state level. But they can also transmit less to inflation than demand and technology shocks when inflation is receding (even if it is well above its steady state). Hence, cost-push shocks generate conditional heteroskedasticity in inflation and inflation risk in our nonlinear model, consistent with the seminal paper by Engle (1982) and the more recent work by López-Salido and Loria (2020). Since these shocks are key drivers of price inflation in our estimated model and commonly believed to have played an important role during the post-COVID period, we argue that our model can account better for inflation dynamics during this period than a standard linearized macroeconomic model. Regression analysis supports the view that cost-push-type shocks have a larger impact on inflation if inflation is high to begin with (see e.g., Gelos and Ustyugova 2017; Forbes, Gagnon and Collins 2021a; Forbes, Gagnon and Collins 2021b; and Ball, Leigh and Mishra 2022).

We establish our main results using the nonlinear formulation of the benchmark Smets and Wouters (2007, SW henceforth) model, which builds on the seminal model of Christiano, Eichenbaum and Evans (2005). The SW model has been shown to have empirical properties that are on par with standard Bayesian vector autoregressions prior to the Great Recession, see e.g. del Negro et al. (2007). The only difference relative to the original SW estimated model is that we follow Harding, Lindé and Trabandt (2022) and use the nonlinear formulation of the SW model allowing for a more prominent role for Kimball (1995) quasi-kinked demand in goods markets. The more prominent role for quasi-kinked demand increases the marginal data density provided that the average markup aligns with micro- and macroeco-

conomic empirical evidence. Recent work by Dupraz (2017) and Ilut et al. (2022) provides a microfounded theory of kinked demand.

An important policy implication from our analysis is that the central bank faces a more severe trade-off between inflation and output stabilization when inflation is elevated. This finding is driven by the fact that cost-push shocks propagate more strongly to inflation than monetary policy shocks when inflation is surging above the central banks inflation target. We use the nonlinear model to filter data up to 2022Q1 and then examine the propagation of positive cost-push and monetary policy shocks given the filtered state. Because inflation is elevated at this state, the nonlinear model implies a twice as large jump in inflation compared to the standard linearized model in response to the cost-push shock. The larger transmission to inflation implies that the central bank endogenously, through its policy rule, tightens the policy rate by twice as much. As a result of the tighter policy stance and the elevated level of inflation, the output gap falls nearly twice as much in the nonlinear model compared to the linearized model. If the central bank chooses to fully offset the pass-through to inflation, the required policy tightening triggers large output costs although policy is more effective than in normal times in the nonlinear model. Conversely, if the central bank chooses to fully stabilize the output gap, the resulting surge in inflation due to cost push shocks will be much larger in the nonlinear model than in the linearized model.

Our results rest on two key model elements. First, we introduce real rigidities in price setting. To do this, we follow Dotsey and King (2005) and Smets and Wouters (2007) and use the Kimball (1995) aggregator instead of the standard Dixit and Stiglitz (1977) aggregator. The Kimball aggregator introduces additional strategic complementarities in firms price setting behavior, which lowers the sensitivity of prices to marginal cost for a given degree of price-stickiness. As such, the Kimball aggregator is commonly used in New Keynesian models, see e.g. Smets and Wouters (2007), as it allows to simultaneously account for the macroeconomic evidence of a low Phillips curve slope and the microeconomic evidence of frequent price changes.

Second, we argue that the standard procedure of linearizing all equilibrium equations around the steady state, except for the zero lower bound (ZLB) constraint on the nominal

interest rate, introduces large approximation errors when large shocks hit the economy as was the case during the Great Recession and the post-COVID period. Implicit in the linearization procedure is the assumption that the linearized solution is accurate even when far away from the steady state. Our analysis shows that the linearized solution is very inaccurate when far away from the steady state. In particular, we show that cost-push shocks can propagate more than four times stronger in the nonlinear model relative to the linearized model when inflation is high. We show that the nonlinearity implied by the Kimball aggregator is a key model feature that accounts for the differences between the linearized and nonlinear model solutions. The Kimball aggregator implies that the demand elasticity for intermediate goods is state-dependent, i.e. firms' demand elasticity is an increasing function of their relative price and the demand curve is quasi-kinked. Due to the rising demand elasticity, firms' marginal revenues are a concave function of their prices. Consequently, the optimal price setting becomes asymmetric, since firms equate marginal revenue to marginal cost. If the latter rise or fall, the resulting optimal price setting becomes asymmetric in the sense that firms find it optimal to increase prices more than to decrease them. While the fully nonlinear model takes the state-dependence of the quasi-kinked demand curve explicitly into account, a linear approximation replaces this key nonlinearity by a linear function. When the economy is exposed to large shocks, the state-dependence of the quasi-kinked demand curve becomes quantitatively important and the linear approximation ceases to provide accurate results.

Importantly, the Phillips curve nonlinearities implied by our model remains relevant for inflation fluctuations induced by supply shocks.² Put differently, our key results are not contingent on demand shocks driving a surge in inflation but are robust to supply shocks being the key driver of rising inflationary pressures. Hence, the sensitivity of inflation to economic shocks in both demand and supply shock driven inflation surges is amplified in the nonlinear model compared to the linearized model.

All told, our key contribution is to provide a structural general equilibrium model which can jointly account for the small drop in inflation during the Great Recession and the large

² Throughout the paper we use supply shocks and cost-push or markup shocks interchangeably. That is, we define supply shocks to move output and inflation in opposite directions while demand shocks drive output and inflation in the same direction.

surge in inflation during the post-COVID period.

An important policy implication of our work is that although the Phillips curve steepens when inflation is elevated it does not mean that it is easier for the central bank to manage inflation-output trade-offs. The key reason is that the impact of adverse cost push shocks on inflation is amplified when inflation is high. So, although interest rate policy becomes more effective when inflation is elevated, adverse cost push-shocks also propagate more strongly to inflation and output in such a situation. In other words, even if the slope of the Phillips curve is steeper and monetary policy is more effective to deal with demand shocks, the Phillips curve shifts up more when further adverse cost-push shocks hit the economy which worsens the inflation-output tradeoff for the central bank.

The remainder of the paper is organized as follows. Section 2 presents a stylized static model of optimal price setting with kinked demand that conveys the key mechanism driving our results. Section 3 presents the workhorse macroeconomic model with real rigidities in a dynamic stochastic general equilibrium framework with nominal price and wage stickiness. Section 4 discusses our results. Finally, section 5 provides concluding remarks.

2 Optimal Price Setting with Quasi-Kinked Demand

In this section, we provide intuition about firms' optimal price setting behavior when the demand curve is quasi-kinked. We consider a stylized static model to convey the intuition why firms increase their prices by more when marginal costs go up compared to the case when marginal costs fall.

Firms maximize profits, π :

$$\pi = p * y - mc * y$$

subject to the following quasi-kinked demand curve:

$$y = a - p^b,$$

where p denotes the nominal price, y denotes the quantity, mc denotes nominal marginal

costs, and $a, b > 0$ are parameters of the demand function. The functional form of the demand function follows e.g. Kimball (1995) as has been used by Harding, Lindé and Trabandt (2022), among many others. The elasticity of demand is given by:

$$\varepsilon \equiv -\frac{dy}{dp} \frac{p}{y} = \frac{b}{\frac{a}{p^b} - 1},$$

which is increasing in the price, p .

Optimal price setting results in the following first order condition:

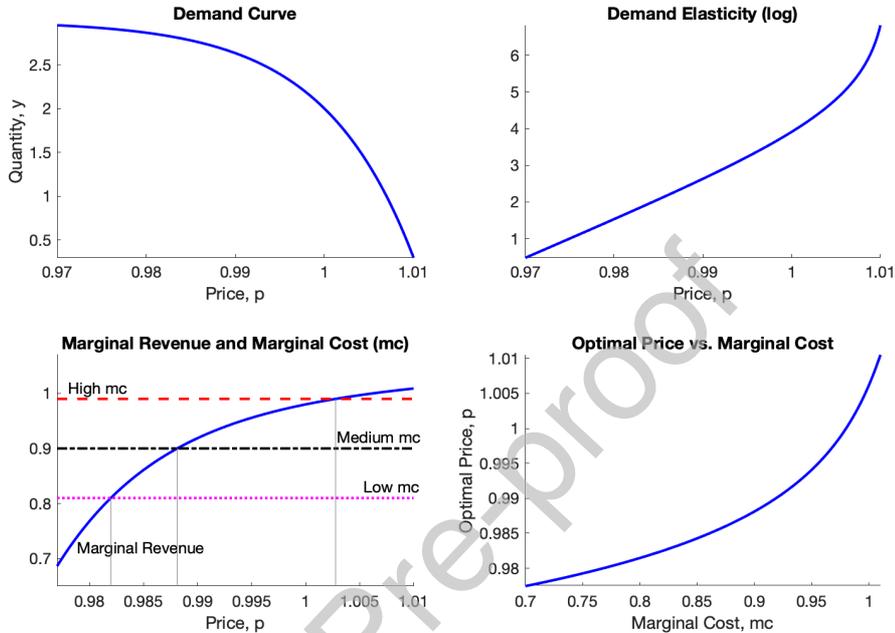
$$p \underbrace{\left[1 - \frac{1}{b} \left(\frac{a}{p^b} - 1 \right) \right]}_{\text{marginal revenue}} = mc$$

Note that marginal revenue is a concave function of the price which is due to the increasing elasticity of demand. As an example, consider the following parameter values which are broadly in line with the parameterization of the workhorse model in Section 3: $a = 3, b = 100$ and $mc = 0.9$.

Figure 1 shows the demand curve and the elasticity of demand in the top panels. The bottom left panel shows marginal revenue as a function of the price for low, medium and high marginal costs. Note that for a given percentage change in marginal costs, firms increase their prices by more than they cut their prices. This is because firms intend to stabilize their markups. When marginal costs are low, the markups are high and firms have little incentive to cut their prices, especially when demand is quasi-kinked; that is, firms cannot crowd in a lot of extra demand by cutting their prices. When marginal costs are high, markups are low and firms have a large incentive to increase their prices – even when this entails a substantial drop in demand. Note that the concavity of marginal revenue (which results from the rising elasticity of demand as a function of the price) is key for the asymmetric pricing behavior. Finally, the bottom right panel shows the optimal price as a function of the marginal cost, showcasing a convex banana-type optimal pricing schedule as a function of marginal cost. This nonlinear relationship between marginal costs and optimal price setting is the key force that will generate our nonlinear Phillips curve in the dynamic general equilibrium model

that we consider in the next section.

Figure 1: Optimal Price-Setting With Quasi-Kinked Demand



3 The Workhorse Macroeconomic Model

In this section we present the workhorse macroeconomic model that we argue is useful to understanding how nonlinearities in real rigidities in price and wage setting affect inflation dynamics in a quantitatively realistic model environment. Specifically, we use the workhorse Smets and Wouters (2007) model of the US economy which is a multi-shock version of the seminal model of Christiano, Eichenbaum and Evans (2005) with endogenous capital accumulation. We introduce real rigidities in price and wage setting using the Kimball (1995) aggregator following Dotsey and King (2005) and Levin, López-Salido and Yun (2007).³

In the following, we first give a brief overview of the model with a focus on the pricing block of the model and how we compute the linearized and nonlinear solutions of the model.

³ Aruoba, Oue, Saffie, and Willis (2022) construct a menu-cost model with Kimball aggregation and idiosyncratic demand and supply shocks that is able to generate sizable monetary non-neutrality and is consistent with micro pricing evidence.

Appendix A provides a detailed description of the model environment, as well as the resulting linearized and nonlinear equations.

3.1 Model Overview

The workhorse model of Smets and Wouters (2007) features monopolistic competition in the goods and labor markets and nominal frictions in the form of sticky prices and wages. However, it allows non-optimizing firms (households) to index prices (wages) to a composite of steady-state and lagged inflation.⁴ Households can also save in physical capital, with a one-period time to build before new investments turns into productive capital. The model also features several real rigidities in the form of habit formation in consumption, investment adjustment costs, variable capital utilization, and fixed costs in production. The model dynamics are driven by seven structural shocks. Monetary policy shocks follow an $AR(1)$ process and two additional inefficient cost-push shocks in wage and price setting follow an $ARMA(1,1)$ process. Four efficient shocks (total factor productivity, risk premium, investment-specific technology, and government spending shocks) follow $AR(1)$ processes. The exact specifications of the nonlinear model and its linearized representation are described in detail in Appendix A; here we present the linearized and nonlinear pricing equations that are central for our paper.

The linearized Phillips curve in the SW model is given by

$$\begin{aligned}\widehat{\pi}_t - \iota_p \widehat{\pi}_{t-1} &= \beta (E_t \widehat{\pi}_{t+1} - \iota_p \widehat{\pi}_t) + \kappa \widehat{m}c_t + \widehat{\epsilon}_{p,t}, \\ \kappa &= \frac{(1 - \xi_p \beta)(1 - \xi_p)}{\xi_p (1 + (\phi_p - 1)\epsilon_p)}\end{aligned}\quad (1)$$

where $1 - \xi_p$ is the probability of each firm being able to reoptimize the price each period, ϵ_p is the curvature of the Kimball aggregator function, ϕ_p is the steady state gross price markup, and the cost-push, or markup, shock $\widehat{\epsilon}_{p,t}$ has been rescaled with $1/\kappa$ to enter the Phillips curve with a unit coefficient. The corresponding nonlinear recursive pricing equations are

⁴ Hence, while the model embeds non-zero steady state price and wage inflation, it does not feature steady state dispersion in prices and wages. It would be interesting to extend the model to allow for non-indexation to trend inflation.

given by

$$\frac{1 + \phi_p \epsilon_p}{1 + \epsilon_p} p_t^* \gamma_{1,t}^p = \phi_p \gamma_{2,t}^p + \frac{\epsilon_p (\phi_p - 1)}{1 + \epsilon_p} (p_t^*)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1} + 1} \gamma_{3,t}^p, \quad (2)$$

$$\gamma_{1,t}^p = (\delta_t^p)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right)^{-\frac{1+\phi_p \epsilon_p}{\phi_p-1}} \gamma_{1,t+1}^p, \quad (3)$$

$$\gamma_{2,t}^p = (\delta_t^p)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} mc_t \varepsilon_{p,t} y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right)^{-\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} \gamma_{2,t+1}^p, \quad (4)$$

$$\gamma_{3,t}^p = y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right) \gamma_{3,t+1}^p, \quad (5)$$

where the different endogenous variables are defined in the appendix. Importantly, you can see from eq. (4) that the markup shock $\varepsilon_{p,t}$ (which is assumed to have unit mean) in the nonlinear pricing system multiplies marginal costs mc_t . So in this sense, it represents an exogenous shock to the desired markup. In the following, we refer to them as markup or cost-push shocks.

3.2 Calibration and Solution

The model is estimated on seven key macroeconomic quarterly US time series as observable variables: the log-differences of real per capita GDP, consumption and investment, the log-differences of compensation per hour and the GDP deflator, the log-deviations of hours worked per capita from their average, as well as the federal funds rate. Further details about the data and the measurement equations linking the model variables to their data counterparts are provided in the appendix.

SW use full information Bayesian techniques to estimate the model. Bayesian inference starts from a prior distribution that describes the available information prior to observing the data used in the estimation. The observed data is subsequently used to update the prior, via Bayes' theorem, to a posterior distribution of the model's parameters, which can be summarized in the usual measures of location (e.g. the mode or the mean) and spread (e.g. the standard deviation and probability intervals).⁵ We adapt the parameters estimated by

⁵ We refer the reader to Smets and Wouters (2003, 2007) for a more detailed description of the estimation

Smets and Wouters (2007) on pre-Global Financial Crisis and COVID periods data, with the exception of the pricing parameters ϕ_p , ξ_p , and ϵ_p . In particular, we re-estimate the linearized model for the 1965Q1 – 2007Q4 sample, imposing an alternative prior $\phi_p \sim N(1.2, 0.05)$ to obtain a lower gross markup than the 61 percent estimated by SW. Harding, Lindé and Trabandt (2022) show a large body of calibrated or estimated New Keynesian DSGE models that suggest markups that are notably lower than 61 percent. Moreover, we calibrate $\xi_p = 0.667$ in line with micro evidence (which is close to the SW posterior mode of .65) and instead estimate the Kimball curvature parameter using the prior $\epsilon_p \sim N(75, 25)$. This results in a posterior mode where $\epsilon_p = 64.5$ and $\phi_p = 1.34$. In addition, κ in eq. (1) equals .008, which is somewhat smaller than SW’s estimate of .026.⁶ Finally, note that our parameterization of the slope of the Phillips curve is in line with the estimates in Hazell, Herreno, Nakamura and Steinsson (2022).⁷

To compute the linearized and nonlinear solutions, we use the Fair and Taylor (1983) solution algorithm. This algorithm is also known as a two-point boundary value solution or time-stacking algorithm. The Fair-Taylor solution algorithm imposes certainty equivalence on the nonlinear model, just as the linearized model solution does by definition. In other words, the Fair-Taylor solution algorithm allows us to trace out the implications of not linearizing the equilibrium equations, which is exactly our objective. All of the relevant information for solving the nonlinear and linearized models is captured by the current state of the economy, including the contemporaneous realization of the exogenous shocks.

An alternative approach to solve the model would have been to compute solutions where uncertainty about future shock realizations matters for the dynamics of the economy, for example, following Aruoba, Cuba-Borda, and Frank Schorfheide (2018), Adam and Billi (2006, 2007), Fernández-Villaverde et al. (2015), Gust, Herbst, López-Salido and Smith (2017) and Nakata (2017). These authors have shown that allowing for future shock uncertainty

procedure.

⁶ Our lower value for κ partly reflects the different prior and partly the extended sample period (recalling that SW’s sample ends in 2004:4). For our sample period ending in 2007:4, we obtain $\kappa = .018$ with the SW priors. Note that the re-estimated model is associated with an improvement in the marginal likelihood compared to the original SW parameterization by roughly 5 log points.

⁷ See L’Huillier and Phelan (2023) for a recent model in which the degree of price stickiness depends on the type of shocks that hit the economy. Prices are sticky with respect to demand shocks but flexible with respect to supply shocks.

can have potentially important implications for equilibrium dynamics. Importantly, none of these authors have considered a model with Kimball aggregation. Lindé and Trabandt (2018) solve a simplified version of our model with sticky prices and Kimball aggregation under shock uncertainty using global methods, and show that the effects of future shock uncertainty on the global solution of the nonlinear model are quantitatively negligible lending support for using the Fair-Taylor solution method for our baseline results.⁸

As a practical matter, we feed the equilibrium equations of the nonlinear and linearized model into Dynare. Dynare is a pre-processor and a collection of MATLAB routines which can solve nonlinear and linearized dynamic models with forward looking variables. The details about the implementation of the algorithm used can be found in Juillard (1996). We use the perfect foresight/deterministic simulation algorithm implemented in Dynare using the ‘simul’ command.⁹ The algorithm can also easily handle the ZLB constraint: one just writes the Taylor rule including the max operator in the model equations, and the solution algorithm reliably calculates the model solution in fractions of a second.

4 Results

In this section, we report our main results for the linearized and nonlinear solution of the model outlined in the previous section. We begin in Section 4.1 by considering the effects of positive cost-push shocks in long simulations of the model as function of the output gap when the business cycle is driven by demand and supply shocks. Next, we proceed in Section 4.2 to characterize how the transmission of markup shocks vary with the initial inflation level for all the shocks in the estimated SW model. In Section 4.3 we compare the transmission of cost-push and monetary policy shocks in the linearized and nonlinear model in 2022Q1 by filtering the data with the inversion filter on the 7 observable time series 1965Q1 – 2022Q1

⁸ The introduction of wage stickiness and Kimball aggregation in the labor market in the present paper (in addition to price stickiness and Kimball aggregation in the goods market as in Lindé and Trabandt, 2018) should temper the effect of shock uncertainty in the nonlinear model even further. To the extent that allowing for shock uncertainty notably affects the linearized solution, the differences between the linearized and nonlinear solutions we report in this paper are conservative: they would be even larger if we had allowed for shock uncertainty.

⁹ The solution algorithm implemented in Dynare’s simul command is the method developed in Fair and Taylor (1983).

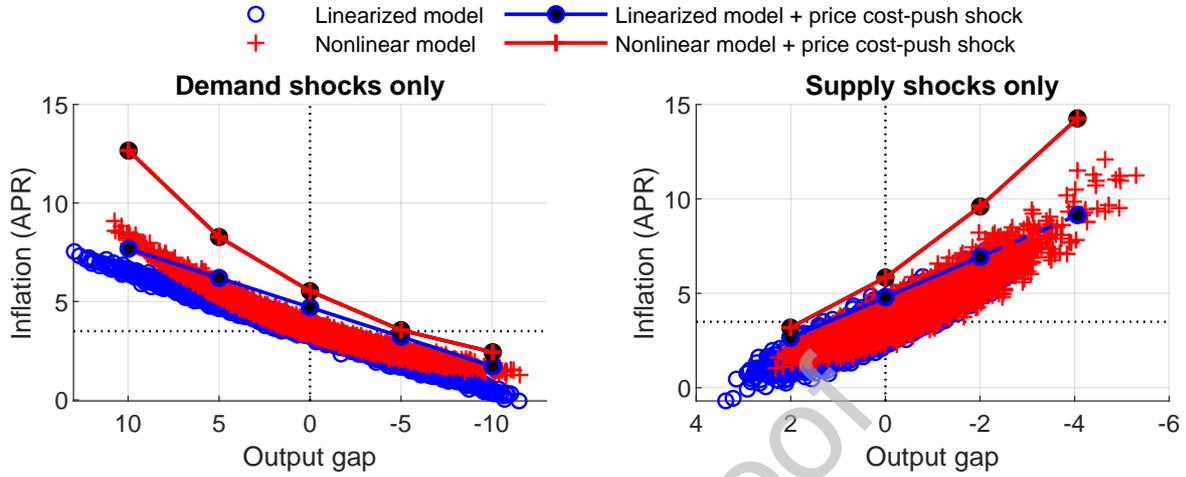
used by Smets and Wouters (2007) when estimating the model. This allows us to characterize monetary policy trade-offs at the current juncture. Finally, in Section 4.4 we study the role of nonlinearities on forecast distributions.

4.1 The Phillips Curve

To understand the differences in the dynamics implied by the linearized and nonlinear solutions, we undertake stochastic simulations of the model for monetary policy shocks ($\varepsilon_{r,t}$) and, separately, for cost-push shocks ($\varepsilon_{p,t}$). We size the standard deviations of monetary policy shocks (σ_r) and cost-push (σ_p) to imply variations in inflation between roughly zero and eight percent in the linearized model. This strategy implies that the size of the monetary policy shocks we consider are notably larger than estimated in the model. Nevertheless we adopt this assumption to demonstrate with a straightforward demand shock the scope of nonlinearities in the model with kinked demand when the economy is far-off the steady state. Interestingly, for the markup shocks, the strategy implies that the size of these shocks is somewhat smaller than in the estimated model. We solve and simulate the linearized and nonlinear model solutions for a long sample of 10,000 periods contingent on exactly the same sequence of shocks $\{\varepsilon_{r,t}\}_{t=1}^{10,000}$ and $\{\varepsilon_{p,t}\}_{t=1}^{10,000}$, disregarding any binding constraints on policy rates in the linearized model.

The blue circles in the left panel in Figure 2 are the simulated inflation and output gap observations in the linearized model, with the output gap on the x-axis (inverted scale) and inflation on the y-axis. The red crosses show the corresponding observations for the nonlinear model solution. The black dotted horizontal and vertical lines indicate the deterministic steady states for inflation and the output gap, respectively. The figure shows a noticeable difference between the linearized and nonlinear model for the relationship between inflation and the output gap. As expected, the linearized model implies a constant downward-sloped Phillips curve whereas the nonlinear solution is associated with a “banana-shaped” Phillips curve, as in the seminal paper by Phillips (1958). This reflects that the Kimball aggregator

Figure 2: Linear and Nonlinear Phillips Curves with Cost-Push Shocks



implies that firms are reluctant to change prices much when relative demand is low.¹⁰ On the other hand, in periods when relative demand is high, firms are more willing to change their prices. As a result, the nonlinear model produces episodes with more elevated price inflation than the linearized solution in which households and firms are equally sensitive to changes in desired price-markups in recessions and booms.¹¹

The blue and red solid lines in the left panel show how the Phillips curves for the linearized and nonlinear solutions shift for positive same-sized markup shocks. These lines are generated by selecting the highest inflation state around economic states with an output gap close to $-10, -5, \dots, 10$. For all those selected states, we simulate the contemporaneous effects when adding same-sized $1.25\sigma_p$ positive markup shocks to the state and then selecting the highest resulting inflation levels in the blue and red dots. This shows how the Phillips curve shifts outward in the linearized and nonlinear model solutions for positive cost-push shocks.

As expected, the transmission of a given-sized markup shock in the linearized model is independent of the output gap level, and the Phillips curve simply shifts outward in parallel. In the nonlinear model, the picture is very different. The nonlinear model implies that a

¹⁰ Costain, Nakov, and Petit (2022) construct a model with state-dependent nominal price and wage rigidities which also implies a flatter Phillips curve slope as trend inflation declines. Their model can account for a substantial share of the decline of the slope of the Phillips curve before the COVID pandemic.

¹¹ Hence, as in Boehm and Pandalai-Nayar (2022), our model implies that responses to shocks are state-dependent and that the Phillips curve is convex.

markup shock shifts out inflation very little when inflation is subdued. When inflation is high, on the other hand, the same-sized markup shock shifts the Phillips curve outward substantially more than in the linearized model. In other words, the transmission of markup shocks are state-dependent and depends importantly on the economic state, lending support for inflation scares in booms (see e.g. Goodfriend, 1993).

In the right panel of Figure 2 we redo the same exercise for supply (cost-push) shocks.¹² As depicted in the Figure, it turns out that supply-side shocks also generate an important nonlinearity. Importantly, and in contrast with demand shocks, cost-push shocks that accelerate inflation trigger output to be below potential (i.e. negative output gaps). An important implication of this is that we don't need an output boom to have increased inflation transmission of cost-push shocks as in the left panel of Figure 2. Our model implies increased propagation also when the output gap is notably negative as shown in the right panel of Figure 2. So the nonlinearity is important even for supply shocks that drive the output gap and inflation in opposite directions.

To solidify the claim that it does not matter per-se whether we have demand or supply driven inflation hikes, and that there is an important interplay between economic activity and baseline inflation in the propagation of cost-push (and demand) shocks, Figure 3 plots the impact effects of a same-sized cost push shock on inflation and the output gap as function of the initial inflation level.

The left column in Figure 3 shows the effects on inflation (upper panel) and the output gap (lower panel) from the same-sized cost-push shocks as a function of the initial level of inflation on the x-axis in the nonlinear model (red line) and the linearized model (blue line) when all variations in the initial inflation level are driven by demand shocks. Based on the results in Figure 2, the output gap will be elevated when underlying initial inflation is solely driven by demand shocks. So, although the output gap is not shown, the impulses in the left column in Figure 3 are computed in an initial state where there is a positive

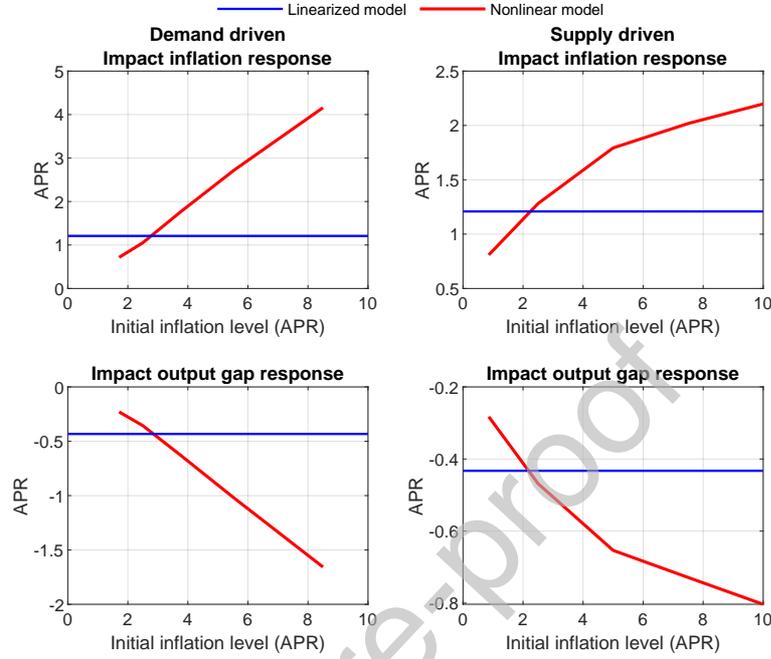
¹² Notice that in the simulation experiment in the right panel of Figure 2, we set the smoothing coefficient ρ_R on the lagged interest rate in the policy rule and the consumption habit persistence parameter \varkappa to nil in order to obtain a strong contemporaneous relationship between inflation and the output gap for supply shocks. As a result, the right panel of Figure 2 is arguably somewhat stylized. That said, Figures 4 and 5 show elevated transmission of cost-push shocks to inflation in the nonlinear model when all parameters are kept at their estimated values (including ρ_R and \varkappa).

relationship between initial inflation and the output gap: the higher initial inflation, the higher the output gap when the cost-push shock hits. The right column in Figure 3 shows the corresponding results when supply shocks are the sole driver of the initial inflation level. In this case, economic activity will typically not be elevated when initial inflation is high. Consistent with the left panel in Figure 2, we see in the upper left panel in Figure 3 that the nonlinear model implies a stronger transmission of cost-push shocks to inflation when the initial inflation level is elevated. Naturally, when inflation is close its steady state level, the results in the nonlinear model and its linearized equivalent coincide. The rising transmission to inflation also implies an increasing negative impact on the output gap when the initial inflation rate is higher. The results in the right column document that the inflationary effects are significantly elevated also in the case when the initial inflation level is driven by supply shocks. An important implication of this finding is that it is not per-se the output gap that is critical in terms of state dependence but rather the initial level of inflation that is the crucial incidence of state dependence. An additional important implication is that the nonlinearity which we stress is relevant regardless whether demand or supply shocks drive the surge in inflation: the output gap can be positive or negative (or something in between if we consider a combination of demand and supply shocks) but the transmission of cost-push shocks increases with the initial level of inflation.

To understand why supply shocks can yield strong propagation effects on inflation even when economic activity is subdued, consider the bottom left subplot of Figure 1 which depicts the convex pricing schedule as a function of marginal cost in the static stylized model discussed in section 2. Now, consider a low price-marginal cost combination to begin with. Starting with an initially low price, a one percent jump in marginal cost leads to a relatively small jump in the new optimal price. Now, consider a much higher initial price-marginal cost combination to begin with. The same sized jump in marginal cost implies now a much larger optimal new price. In other words, in the simple static stylized model, the optimal adjustment price is a convex function of the initial (pre-shock) price.

In the estimated medium-sized model, the optimal price is also a convex function of

Figure 3: Propagation of Cost-Push Shocks in Demand and Supply Driven Expansions and Contractions



the initial (pre-shock) price. In addition, cost push shocks may also propagate somewhat stronger when economic activity is elevated due to demand shocks. This can be seen from the first order optimal price setting conditions (equation 4), in which the product of marginal cost (mc_t) and demand (y_t) appear as a key driving force for the optimal price (i.e. additional to the state variables that ultimately map into the initial level of inflation). This feature is visible when comparing the top left and top right subplots in Figure 3 that show the inflation responses as a function of initial inflation for demand and supply shocks. By comparing the two panels, we see that for given initial inflation, a cost push shock propagates more strongly when the underlying state is driven by demand shocks (and hence demand, y_t , is elevated) compared to supply shocks (and hence demand, y_t , is suppressed).

Figure 2 illustrates that the model embeds a traditional nonlinear Phillips curve when we study the impact of demand and supply shocks separately. Even so, keep in mind that Figures 2 and 3 where drawn for unusually large demand and supply shocks for illustrative reasons. In the next section we will show that the initial level of inflation continues to be

key when we consider the historically relevant drivers of inflation dynamics in the estimated medium-sized DSGE model.

4.2 Propagation of Cost-Push Shocks

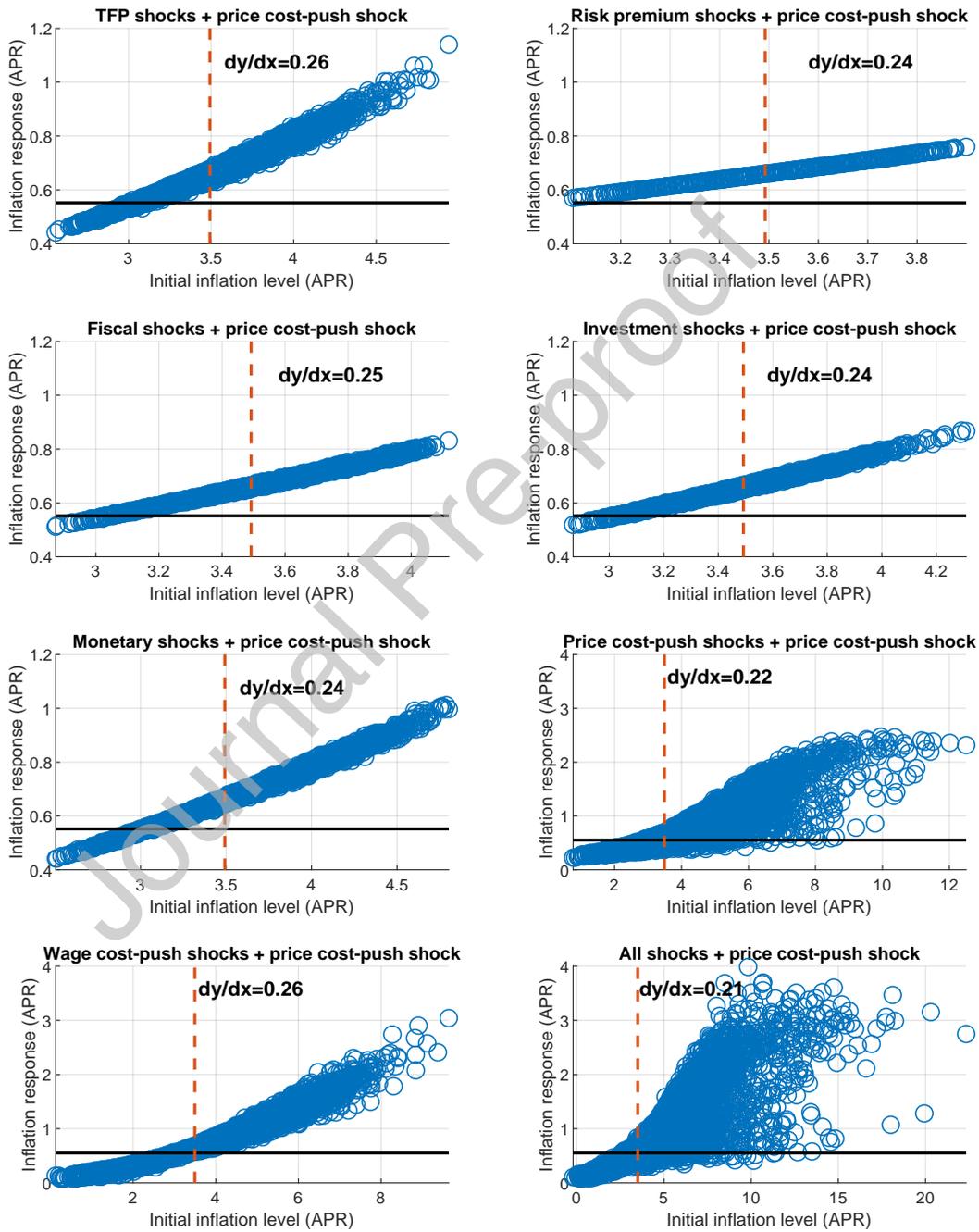
So far, we have established that cost-push shocks propagate stronger in a boom than in a slump, but that there is scope for both demand- and supply-side shocks to trigger amplified inflation dynamics in the nonlinear model. But what about the case when we keep the volatility of shocks at their estimated standard errors based on historical data? In this section we will show that the results hold up when we consider empirically relevant volatility of shocks taken from the estimated linearized Smets and Wouters model, in which wage and price markup shocks account for the bulk of inflation volatility. The analysis will show that propagation of price cost-push shocks is amplified on average regardless of the underlying drivers of inflation, and that a reliable condition for an elevated propagation of price cost-push shocks is that inflation is well above steady state to begin with.

To do this analysis, we begin by simulating the linearized and nonlinear solutions for all seven shocks, with only one shock active at a time in the estimated SW model, using the estimated standard deviations for each shock, for $T = 10,000$ periods. This will provide us with simulated paths of all endogenous variables in the nonlinear $\{y_t^{nonlin}\}_{t=1}^T$ and linearized $\{y_t^{lin}\}_{t=1}^T$ models. Next, we go backwards in time and for each state $t = 1, \dots, 10,000$ add one σ_p positive price cost-push shock and compute its impact on inflation and the output gap. Figures 4 and 5 report the results of this exercise for inflation and output, respectively. Each panel in the figure shows the results when inflation dynamics are driven by each of the seven shocks, whereas the lower right panel shows results when we assume all shocks are active. The x-axis shows the initial inflation level when the price cost-push shock hits, and the y-axis shows the impact this shock has on one-year average inflation.

The upper left panel in Figure 4 shows the effects of a positive price cost-push shock on one-year-ahead inflation when stationary technology shocks are the sole driver of fluctuations in inflation (apart from the cost-push shocks we add at each point in time). The vertical

Figure 4: State-Dependent Effects of Cost-Push Shocks on Inflation

○ Nonlinear model — Linearized model - - - Steady state inflation rate



dashed line shows the deterministic steady state inflation level, while the solid horizontal line shows the impact of the cost-push shocks on one-year-ahead inflation in the linearized model, which is independent on the initial inflation level and the same for all seven shocks. However, in the nonlinear model solution, the impact of a same-size cost-push shock is an upward sloping function of the initial inflation level. The intuition for the larger inflation response in the nonlinear model is provided in Section 2, Figure 1, where we discuss the heightened sensitivity of firms' optimal prices in response to increases in marginal costs. The next four panels in Figure 4, for the risk premium, fiscal spending, investment-specific technology, and monetary shocks feature the same upward sloping line, with dy/dx showing the slope of the regression of the inflation impulse on the initial inflation level in the nonlinear model. The slope is essentially the same for all shocks. The only difference is that the shocks induce unequal fluctuations in the initial inflation levels. The panels for the wage- and price-markup shocks show that these two shocks are most critical for inflation fluctuations in the model as they generate notably more variation in the initial inflation levels. For price-markup shocks, we notice that while the regression line has a similar slope as for the other shocks, there is now considerably larger variation in the transmission of the additional price cost-push shocks. For instance, with an initial inflation rate of 8 percent, the one-year-ahead inflation impulse of the same-sized positive price cost-push shock can be roughly 0.5 or above 2 percent.

The bottom right panel shows the results when simulating all shocks at the same time, which naturally gives rise to even greater variation in the initial inflation levels compared to when simulating each of the seven shocks separately. With all shocks combined, the dispersion increases even further, and for a 10-percent initial inflation level the impact of a positive price-markup shock on one-year-ahead inflation can vary from about 0 to over 3 percent. These results imply that the conditional volatility of inflation is increasing in the inflation level. Hence, there is higher inflation risk when inflation is high, whereas inflation risk is constant in the linearized model solution.

Figure 5 repeats the experiment but, instead, reports the effects on the output gap.¹³ As

¹³ Notice that price cost-push shocks do not affect potential output in the SW model, so the response of the output gap coincides with the response of output.

was the case for inflation, we see that a same-sized markup shock has a more adverse impact on the output gap when the initial inflation level is high, partly because larger transmission of price markup shocks on inflation (which effectively works as a tax by lowering the real wage) but also partly because the elevated transmission precipitates a more vigorous endogenous response of the federal funds rate in our model. The Taylor rule implies that the central bank faced with this adverse trade-off shock endogenously raises the policy rate more when initial inflation is high because it puts more weight on the increased inflationary pressure despite the fact that the adverse supply shock causes a larger deterioration in economic activity when initial inflation is high.

All told, Figures 4 and 5 show that the initial level of inflation continues to be key when we consider the historically relevant drivers of inflation dynamics in the estimated medium-sized DSGE model. When the model is estimated on pre-GFC data, demand shocks do not typically trigger large variations in inflation as can be seen in Figure 4.

But this does not mean that a combination of expansionary demand and adverse supply conditions cannot trigger an inflation surge in our nonlinear model, i.e. a “perfect storm” in which a combination of some unusually large demand and supply shocks initially drives up both inflation and the output gap and make inflation more sensitive to additional disturbances as shown in Figures 2 and 4.

The results shown in Figures 4 and 5 raise the important question about what accounts for the increased inflation risk when inflation is high, i.e. the conditional heteroscedasticity in inflation (as documented to be empirically relevant in the U.K. in the seminal paper by Engle, 1982).¹⁴ Why is the transmission of a positive price cost-push shock so different when the initial inflation level is elevated? To shed light on this issue, Figure 6 reports the effects of identical price cost-push shocks in inflation surges and when inflation is descending for inflation (left panel) and the output gap (right panel). The black line shows the distribution for all shocks in Figure 4, while the red- and blue-dash dotted lines show the effects when inflation is increasing and decreasing, respectively. We separate the impulses in Figure 4 by simply looking at the one-period change in inflation (from $t - 1$ to t) before a markup shock

¹⁴ Our discussant Jeff Campbell pointed out that conditional heteroscedasticity is also a feature of U.S. inflation once the great inflation episode in the 1970s is included in the sample.

hits in period t , and then we separate the responses to a markup shock across the two states: when the change in inflation is positive (inflation is surging) and when it is negative (inflation is descending). We then compute the distribution of the responses in each state. The left panel in Figure 6 shows inflation risk is substantially higher when inflation is increasing before the shock hits. The right panel shows that output is at greater risk when inflation is on the rise, explaining the trumpet-like shape for the output gap responses shown in Figure 5.

4.3 Monetary Policy Trade-offs During the Post-COVID Period

We now turn to make an assessment of the transmission of price cost-push shocks during the post-COVID period and trade-offs for monetary policy to stabilize them. To do so, we filter the shocks in the linearized and nonlinear solutions with the inversion filter described in Fair and Taylor (1983) for the period 1965Q1 to 2022Q1 using US data. Since we have the same number of observables as shocks, the inversion filter provides us with a unique sequence of filtered innovations $\{\varepsilon_{t|t}\}_{t=1}^T$ that maximizes the likelihood for a given parameterization of the linearized and nonlinear model.¹⁵ Given the filtered state in 2022Q1, we study the transmission of price-cost and monetary policy shocks in this quarter. We believe this period is particularly interesting to examine in order to spot differences between the nonlinear and linearized solutions as inflation by the end of 2021 had surged well above the steady state and the Fed's inflation target. Results would be similar if we started in the second half of 2021 or later.

Conditional on period t information, let $X_{t|t}$ denote all variables in the model, except for the innovations to the shock processes $\varepsilon_{t|t}$. The solution of the model is a nonlinear function f such that

$$X_{t|t} = f(X_{t-1|t-1}, \varepsilon_{t|t}), \quad (6)$$

and let y_t be a vector of observables and S a selection matrix that matches the observed

¹⁵ A potential drawback of using the inversion filter is that it does not allow to compute the two-sided innovation (i.e. $\varepsilon_{t|T}$), and hence relies on the one-sided filtered shocks $\varepsilon_{t|t}$ in the analysis. That said, in the linearized solution, the one- and two-sided shocks (the latter being based on a standard Kalman filter) are very similar, suggesting that using the one-sided shocks has a limited impact on the findings.

Figure 5: State-Dependent Effects of Cost-Push Shocks on Output Gap

○ Nonlinear model — Linearized model - - - Steady state inflation rate

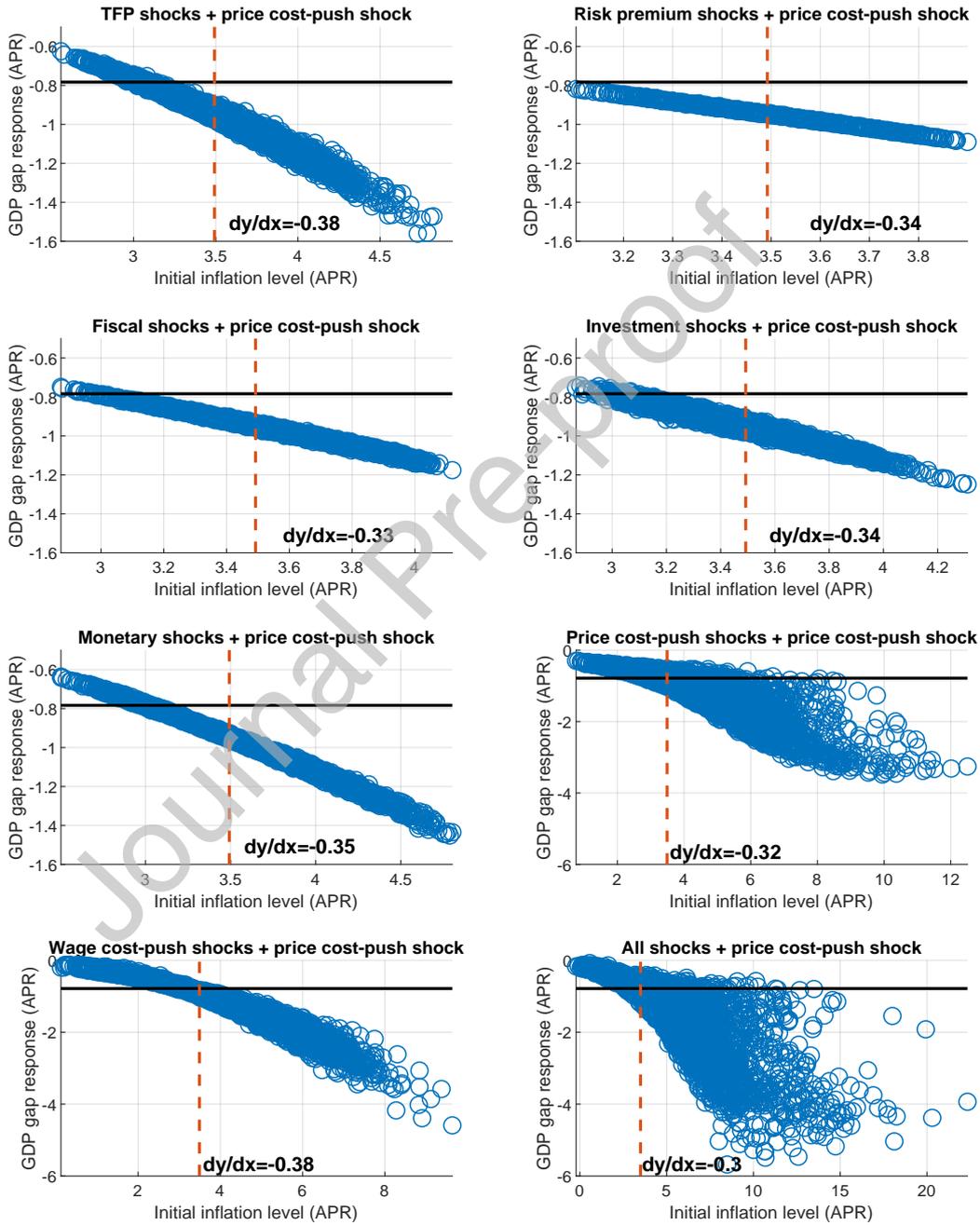
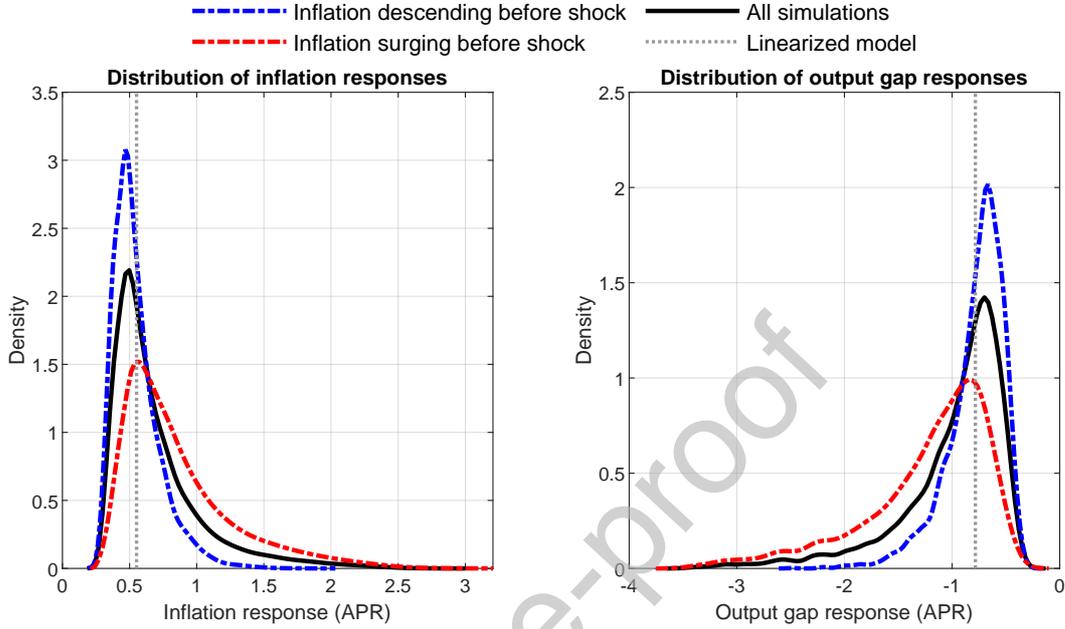


Figure 6: Understanding Inflation Risk: Pass-through of Cost-Push Shocks in Inflation Surge and Descend Episodes

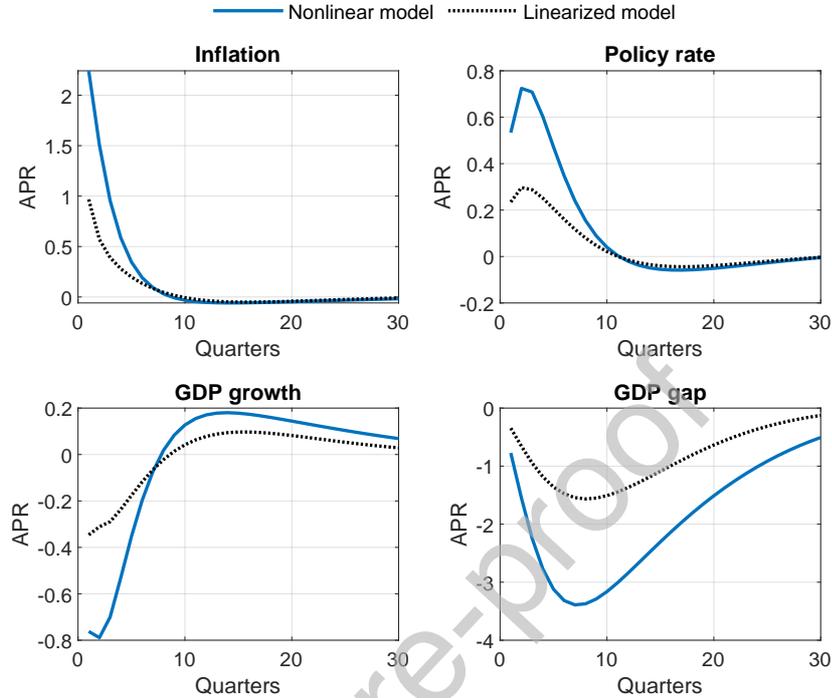


variables to their model counterparts. Then, in each period t we obtain the filtered structural innovations $\varepsilon_{t|t}$, given the data y_t and state of the model $X_{t-1|t-1}$, as the solution to the nonlinear system

$$y_t = Sf(X_{t-1|t-1}, \varepsilon_{t|t}). \quad (7)$$

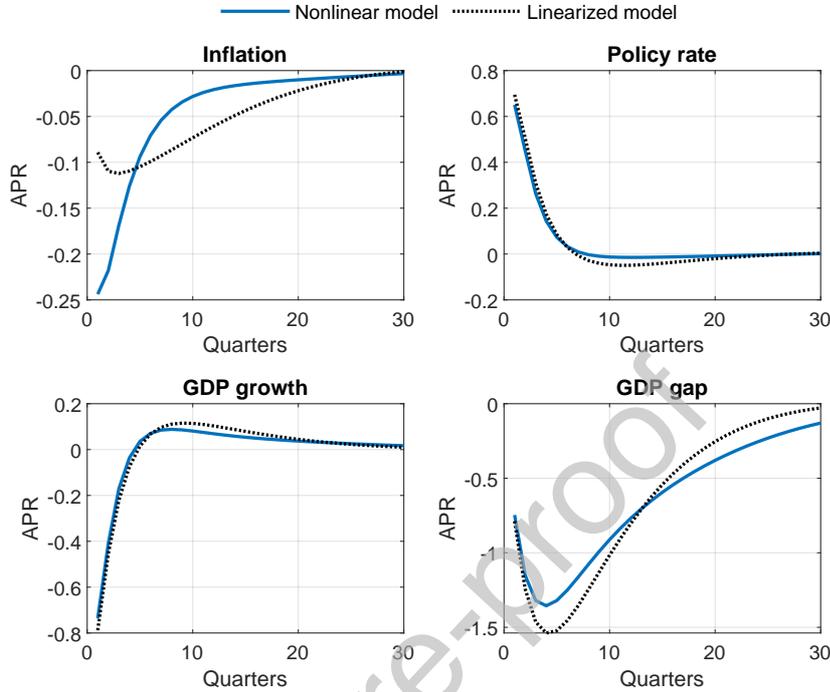
We initialize the filter by running the Kalman smoother on the linearized solution and using the implied Kalman smoothed estimates as initial values for the endogenous variables in the nonlinear filter. However, the nonlinear model contains some additional endogenous state variables (i.e. price and wage dispersion terms), and we initialize these endogenous variables together with the shock innovations $\varepsilon_{t|t}$ so that the nonlinear model matches the observed variables in y_t .

Importantly, we impose the ELB for the federal funds rate when filtering the shocks in the nonlinear model. In the linearized model, we do not impose an effective lower bound through

Figure 7: IRFs to a 1σ Cost-Push Shock in Linearized and Nonlinear Model in 2022Q1

a nonlinear policy rule, so the linearized solution will only prevent the current policy rate from falling below the effective lower bound (ELB) through unanticipated policy innovations. Since the quarterly average for the periods 2009Q1 – 2014Q2 and 2020Q2 – 2022Q1 is not exactly zero and fluctuates a couple of basis points, we adjust the federal funds rate to exactly 10 (annualized) basis points for those quarters. Accordingly, the monetary policy rule in the model is constrained by an ELB of 10 (annualized) basis points. One important caveat of using this filtering approach is that, since monetary policy shocks become inconsequential in the model when the ELB is binding, it is not possible to filter these shocks during the ELB period. Following Guerrieri and Iacoviello (2017) we assume these shocks to be zero when the ELB is binding, except when the model-implied interest rate is predicted to be above the ELB and a monetary policy shock is necessary to obtain an exact match between the observed data and the model counterparts.

Given the filtered states in 2022Q1 in the linearized and nonlinear models, we then add a

Figure 8: IRFs to a 1σ Monetary Shock in Linearized and Nonlinear Model in 2022Q1

one σ_p price cost-push and σ_r monetary policy shocks to the linearized and nonlinear models, respectively. Figure 7 shows the resulting impulse response functions for the price markup shocks in the linearized and nonlinear model solutions as of 2022Q1. Of course, the results in the linearized model are invariant to the filtered state and the average of the first four quarters in the figure equals 0.55 (black horizontal line in Figure 4). For the nonlinear model, we see that the shock's effect is more than twice as large over the first year on inflation and the output gap, despite a twofold increase in the policy rate relative to the linearized model.

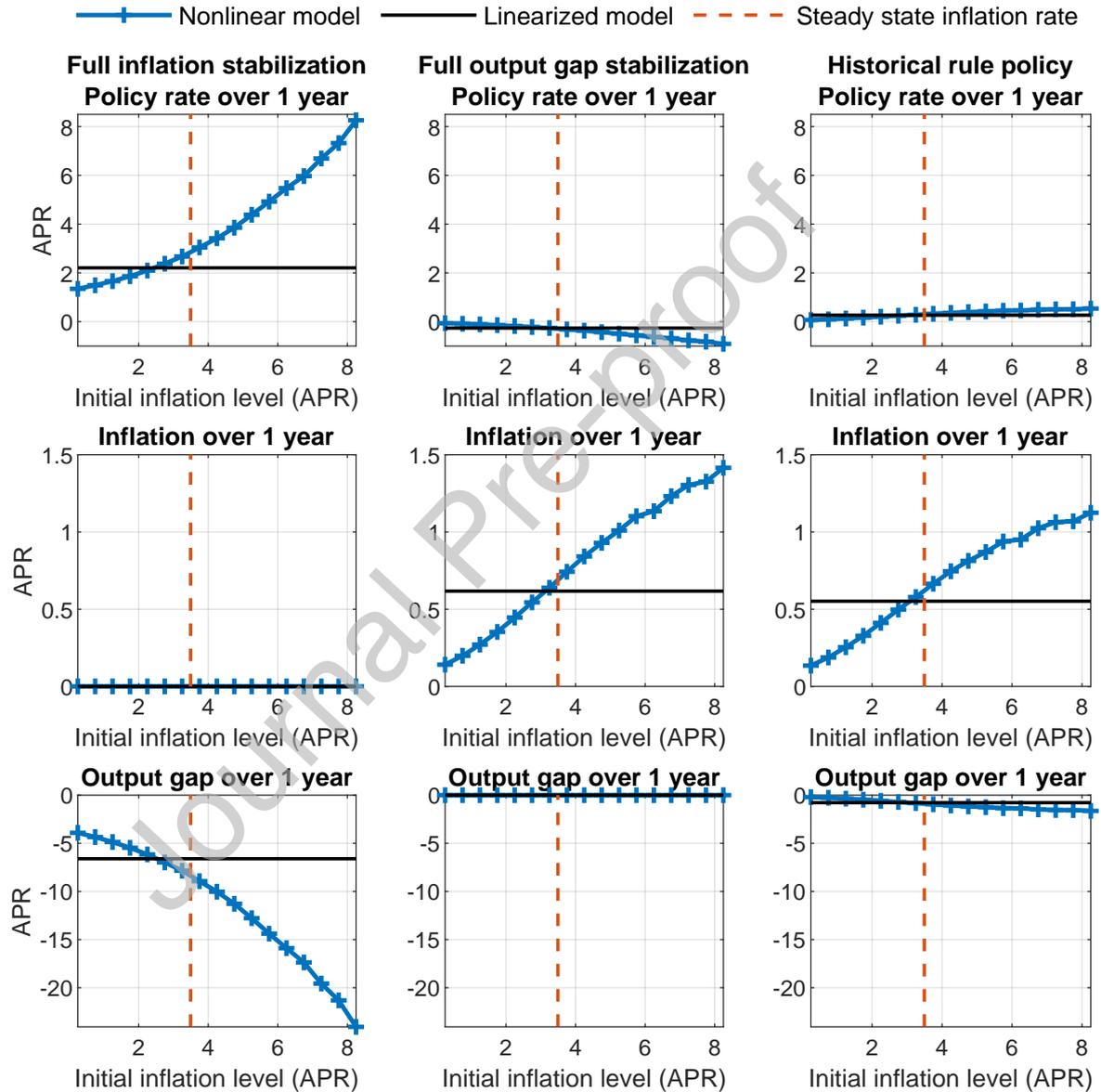
In Figure 8, we show the corresponding effects of a monetary policy shock. The figure shows that a monetary policy shock has the same effect on output gap and output growth, but the impact on inflation is about twice as high initially relative to the linearized model. Even so, the model implies a rather unfavorable monetary policy inflation-output gap trade-off. To reduce inflation by 0.1 percentage points the policy maker needs to accept a decline of more than 1% in the output gap over one year. Figure 7 implies this trade-off is further exacerbated in the nonlinear model in the current situation of high inflation risk, as it takes

even tighter monetary policy than shown in the figure to maintain a pass-through of price cost-push shocks to inflation at normal levels according to our estimated model.

To demonstrate the more unfavorable monetary policy trade-off when inflation is elevated, Figure 9 reports the required policy tightening, in addition to that prescribed by the endogenous reaction according to the estimated rule, during the first year, to fully stabilize any impulses to one-year-ahead inflation from a one standard deviation price cost-push shock as a function of the initial inflation level. For the linearized model, the tightening needed is invariant to the initial inflation level and is a little more than two percent, on average, to stabilize inflation during the first year following a price-markup shock. This magnitude can be derived by combining the impulses in the linearized model for inflation and the policy rate in Figures 7 and 8 (i.e., how big a policy rate movement is required, according to Figure 8, to remove the 0.55 average increase in inflation shown in Figure 7 in the linearized model). The output cost of such an inflation-nutter policy is fairly large, a little above 6 percent in the linearized model. The blue line with crosses plots the corresponding interest rate tightening and output cost in the nonlinear model. As in Figure 2, we compute this trade-off curve as averages for states clustered around certain initial inflation levels. As is evident from the model, the nonlinear formulation of the model implies increasing adverse trade-offs to stabilize inflation, even though the nonlinear model implies that monetary policy has a stronger effect on inflation when inflation is high. This adverse trade-off is driven by the fact that even though both monetary policy and price-markup shocks become equally more potent as functions of the initial inflation rate on average, the price markup shocks have much larger absolute effects and, hence, increasingly more policy tightening is needed to keep inflation in check as the initial inflation level increases.

To highlight the trade-offs for inflation and output gap stabilization in response to the cost-push shocks, the middle panel of Figure 9 shows results under full output gap stabilization, which complements the previous results under full inflation stabilization. The right panel of Figure 9 also reports results when the central bank conducts monetary policy following the estimated Taylor rule, i.e. the historical policy conduct in our sample.

Figure 9: Tradeoffs for Interest Rate Policy:Tightening and Output Cost for Alternative Inflation Stabilization Scenarios



Importantly, the figure shows that if monetary policy does not act vigorously to counteract cost-push shocks, such shocks will propagate more strongly to inflation, especially when initial (pre-shock) inflation is high. Moreover, by comparing the outcomes under the historical rule (right panel) with those under full output stabilization (middle panel), it appears as if the historical (estimated) policy rule implies a strong focus on output gap stabilization. The cases of full inflation and output gap stabilization can be viewed as polar cases of optimal monetary policy considerations. That said, studying the implications of optimal monetary policy is beyond the scope of the paper and we leave this important matter for future research.

4.4 Conditional Forecast Distributions

As a final exercise, we study the impact of the nonlinear solution on the conditional forecast distributions. To do this, we follow the filtering procedure outlined in Section 4.3, and obtain filtered states for $T = \{2020Q4, 2021Q2, 2021Q4, 2022Q1\}$. Given the filtered state in T (based on data up to period T), we then construct conditional forecast distributions for periods $T + 1, \dots, T + h$ by computing 1,000 dynamic forecasts in which economic shocks hit as surprises during the forecast horizon. We report results for both the nonlinear and linearized solutions in Figure 10, but in order to tease out the impact of the nonlinearities in the solution and to consider an identical initial state, we base the projections on the filtered state in the linear model.¹⁶ An additional technical difference is that the nonlinear model imposes the ELB on the policy rate, whereas the linearized model allows the policy rate to become negative.¹⁷

As can be seen from Figure 10, the median forecast in the linearized and nonlinear models differs very little in 2020Q4. This is because inflation is close to the steady state at the initial state in this quarter. Even so, the lower uncertainty bands differ notably as infla-

¹⁶ Alternatively, we could have based the initial state on the nonlinear model, but this would have required setting all nonlinear state variables in period T in the linearized model to nil when doing the forecasts. Of course, we could also have conditioned the forecasts on the filtered state in each of the models, but doing so would not allow us parse out the role of the nonlinearities per se, because the initial state would differ.

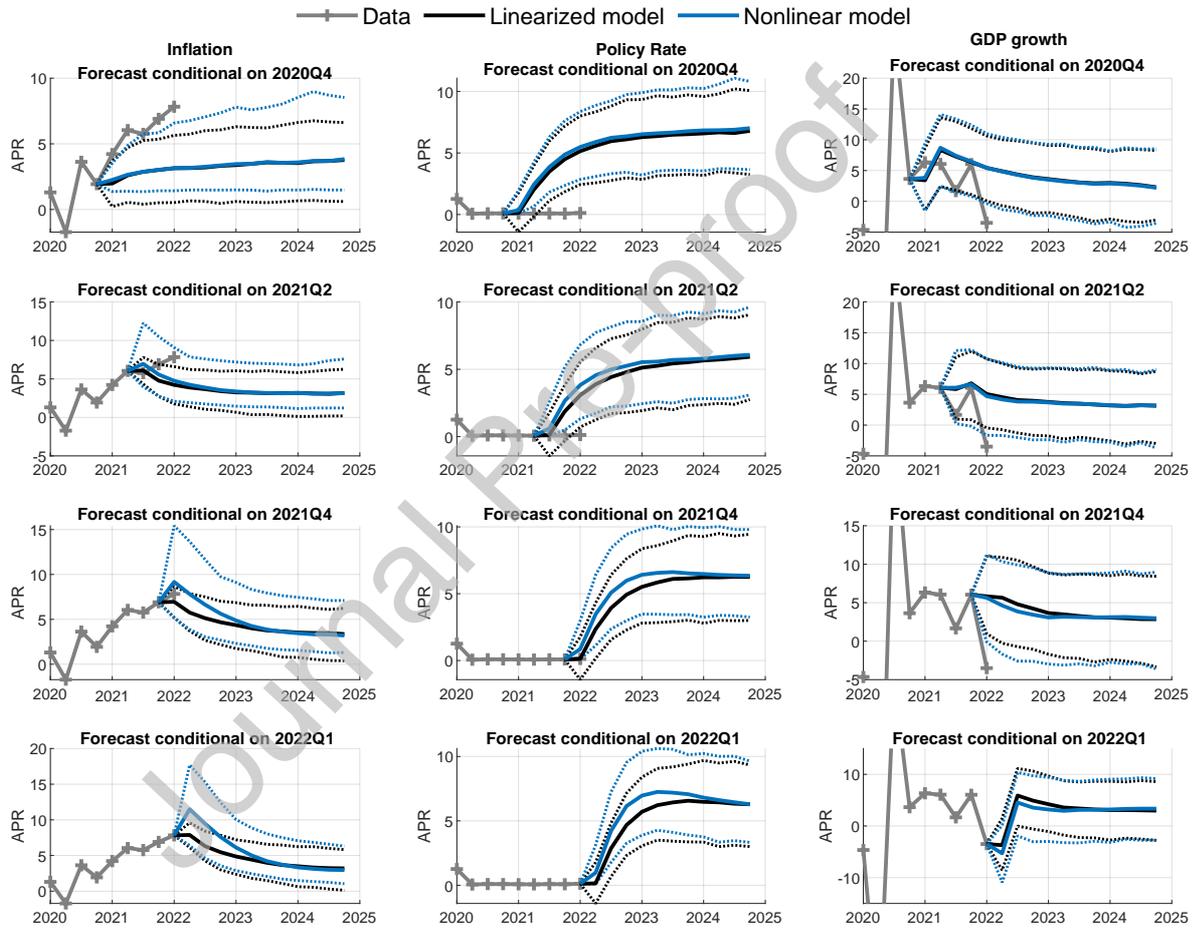
¹⁷ However, as indicated by the uncertainty bands for the linearized model in Figure 9, the probability of a binding ELB is low. Hence, this alternate assumption plays a minor role for any differences between the conditional forecast distributions for the linearized and nonlinear models.

tion can generally become persistently negative in the linearized model, although not for the 5th percentile given this initial state. The nonlinear model, on the other hand, implies that shocks have less impact on inflation when inflation becomes lower and hence there is a noticeable reduction in the deflation probability in this variant of the model. Given the state in 2020Q4, both models underpredict the subsequent uptick in inflation, but it should be noted that the model forecasts are contingent on a quick and sharp normalization of the policy rate. Had we instead imposed a constant interest rate path (in line with the data), the gap between predicted and actual inflation outcomes would have been narrowed. So, our model suggests that loose U.S. monetary policy is likely to have had an important role in driving post-COVID inflation dynamics. While macroeconomic models cannot capture all aspects of reality, our estimated workhorse macroeconomic model suggests that the federal funds rate was likely kept too low for too long and that this likely contributed to the inflation surge in 2021.

Moving onto the later quarters, we see that as the initial inflation level rises, the differences between the nonlinear and linearized models increase. In particular, the nonlinear model implies notably higher near-term inflation risk and hence a notably higher median inflation forecast, especially in the second-half of 2021 and the beginning of 2022. The higher near-term inflation risk also translates into higher median policy rate projections, as well as an elevated risk of a notably tighter policy rate stance in the nonlinear model. As a result, the nonlinear model implies somewhat more downside risk to output growth in the conditional distributions as in Adrian et al. (2019).

Finally, an overall impression from Figure 10 is that inflation risk in the nonlinear model is mostly a near-term phenomenon. After two years, most of the differences between the nonlinear and linearized conditional distributions have dissipated. Two key reasons for this finding is the $ARMA(1,1)$ feature of the price- and wage cost-push shocks and the modest role for intrinsic persistence in the estimated wage and price setting curves in the SW model. Both these features of the estimated model imply that the price-wage cost-push shocks have transient effects on the economy. Alternative assumptions about these parameters could give

Figure 10: Conditional Forecast Distributions Given Filtered State in Linearized Model



rise to more persistent differences in conditional forecast distributions.

To provide a further metric to assess the quantitative performance of the nonlinear model relative to its linearized equivalent, Figure 11 shows the filtered (model-based) shocks and outcomes during the post-COVID period. The left panel shows the filtered price cost-push shocks needed to explain inflation outcomes 2021Q1-2022Q1 based on the filtered state of the linearized model in 2020Q4 as an initial condition for both the linearized and nonlinear model. We use the same initial state in 2020Q4 to set both models on an equal footing. The results show that the nonlinear model – with the exception of 2021Q1 when inflation was still close to steady state – requires a string of notably smaller positive shocks than the linearized model to explain the surge in inflation.

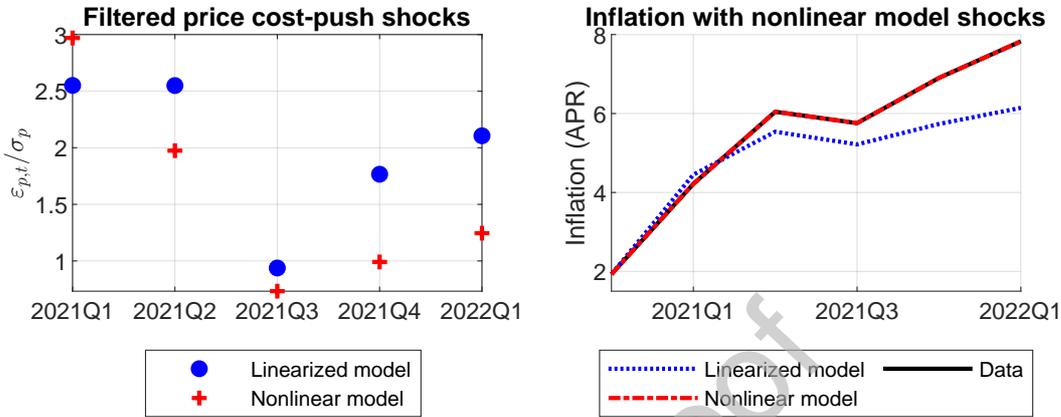
We then feed all filtered shocks from the nonlinear model to the linearized model, starting from 2020Q4 to obtain an inflation counterfactual in the linearized model. The resulting counterfactual path of inflation is provided by the blue dotted line in the right panel of Figure 11.¹⁸ This exercise demonstrates that the smaller filtered shocks in the nonlinear model are associated with bigger inflation amplification effects, i.e. the nonlinear model can better explain the surge in inflation during the post-COVID period with smaller cost-push shocks (with the exception of 2021Q1 as noted earlier). The results in Figure 11 complement our previous results in Figure 10, which suggest that the nonlinear model is better at forecasting one-year ahead inflation than its linearized equivalent.

5 Conclusions

We propose a macroeconomic model with a nonlinear Phillips curve that is flat when inflationary pressure is subdued and steep when inflationary pressure is elevated. The nonlinear Phillips curve in our model arises due to a quasi-kinked demand schedule for goods produced by firms. Our model can jointly account for the modest decline in inflation during the Great Recession and the surge in inflation during the Post-COVID period. Because our model

¹⁸ Notice that the red dash-dotted line from the nonlinear solution is on top of actual inflation outcomes. This is expected given that the innovations have been filtered in the nonlinear model.

Figure 11: Filtered Cost-Push Shocks and Inflation in Linearized and Nonlinear Model During Post-COVID Period



implies a stronger transmission of shocks when inflation is high, it generates conditional heteroskedasticity in inflation and inflation risk. Hence, our model can generate more sizeable inflation surges due to cost-push and demand shocks than a standard linearized model. Finally, our model implies that the central bank faces a more severe trade-off between inflation and output stabilization when inflation is high.

An important implication of our work is that although the Phillips curve steepens when inflation is elevated it does not mean that it is easier for the central bank to manage inflation-output trade-offs. The key reason is that the impact of adverse cost-push shocks on inflation is amplified when inflation is high. So, although interest rate policy becomes more effective when inflation is elevated, adverse cost push shocks also propagate more strongly to inflation and output in such a situation. In other words, even if the slope of the Phillips curve is steeper and monetary policy is more effective to deal with demand shocks, the Phillips curve shifts up more when further adverse cost-push shocks hit the economy which worsens the inflation-output tradeoff for the central bank.

We leave several important issues for future work. For instance, it would be of interest to study the role of nonlinearities to understand the great inflation of the 1970s. It would also be of interest to explore the implications for optimal monetary policy of kinked demand, extending the work of e.g. Levin, López-Salido, Yun (2007) and Levin, López-Salido, Nel-

son, and Yun (2008). Moreover, it would be important to extend the model to allow for endogeneity between inflation drivers and policy responses. We retained the conventional assumption that all variation in price and wage cost-push shocks is exogenous with respect to policy conduct, but it would be of interest in future work to consider an environment where monetary policy can influence the drivers of inflation (i.e. a strong tightening can lower energy prices). Moreover, our analysis imposed the conventional rational expectations assumption, and it would be interesting to explore how non-rational expectations or a de-anchoring of inflation expectations as proposed by Beaudry et al. (2022) may affect inflation dynamics under quasi-kinked demand.

References

- Adam, Klaus, and Roberto M. Billi (2006), “Optimal Monetary Policy under Commitment with a Zero Bound on Nominal Interest Rates”, *Journal of Money, Credit, and Banking* 38(7), 1877-1905.
- Adam, Klaus, and Roberto M. Billi (2007), “Discretionary Monetary Policy and the Zero Lower Bound on Nominal Interest Rates”, *Journal of Monetary Economics* 54(3), 728-752.
- Adjemian, Stéphane, Matthieu D. Paries, and Stéphane Moyene (2008), “Towards a monetary policy evaluation framework”, European Central Bank Working Paper Series No. 942.
- Adrian, T., N. Boyarchenko, and D. Giannone (2019), “Vulnerable Growth,” *American Economic Review* 109(4), 1263-89.
- Aruoba, S. Boragan, Pablo Cuba-Borda, and Frank Schorfheide (2018), “Macroeconomic Dynamics Near the ZLB: A Tale of Two Countries”, *Review of Economic Studies* 85(1), 87–118.
- Aruoba, S. Boragan, Eugene Oue, Felipe Saffie, and Jonathan L. Willis, (2022), “Real Rigidities, Firm Dynamics and Monetary Non-Neutrality: Role of Demand Shocks”, *Manuscript*.
- Ball, Laurence, Daniel Leigh and Prachi Mishra (2022), “Understanding U.S. Inflation During the COVID Era” NBER Working Paper No. 30613.
- Beaudry, Paul, Thomas J. Carter and Amartya Lahiri (2022). “Looking Through Supply Shocks versus Controlling Inflation Expectations: Understanding the Central Bank Dilemma,” Staff Working Papers 22-41, Bank of Canada.
- Boehm, Christoph E., and Nitya Pandalai-Nayar, (2022), “Convex Supply Curves”, *American Economic Review*, 112 (12): 3941-69.
- Calvo, Guillermo, “Staggered Prices in a Utility-Maximizing Framework,” *Journal of Monetary Economics*, 1983, 12(3), pp. 383-98.
- Christiano, Lawrence J., Martin Eichenbaum and Charles Evans (2005), “Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy”, *Journal of Political Economy*

113(1), 1-45.

Costain, James, Anton Nakov, Borja Petit, (2022), “Flattening of the Phillips Curve with State-Dependent Prices and Wages”, *The Economic Journal*, Volume 132, 546–581.

Del Negro, Marco, Frank Schorfheide, Frank Smets, and Rafael Wouters, 2007, “On the Fit of New Keynesian Models.” *Journal of Business & Economic Statistics* 25 (2): 123–43.

Dixit, Avinash K, and Joseph E. Stiglitz (1977), “Monopolistic Competition and Optimum Product Diversity”, *American Economic Review* 67(3), 297-308.

Dotsey, Michael and King, Robert G., (2005), “Implications of state-dependent pricing for dynamic macroeconomic models,” *Journal of Monetary Economics* 52(1), 213-242.

Dupraz, Stéphane, (2017), “A Kinked-Demand Theory of Price Rigidity”, Manuscript.

Engle, Robert F. (1982), “Autoregressive Conditional Heteroscedasticity with Estimates of the Variance of United Kingdom Inflation,” *Econometrica* 50(4), 987-1007.

Fair, Ray C. and John B. Taylor (1983), “Solution and Maximum Likelihood Estimation of Dynamic Rational Expectations Models”, *Econometrica* 51(4), 1169-1185.

Fernández-Villaverde, Jesús, Gordon, Grey, Guerrón-Quintana, Pablo and Juan F. Rubio-Ramírez (2015), “Nonlinear Adventures at the Zero Lower Bound”, *Journal of Economic Dynamics and Control* 57, 182–204.

Forbes, Kristin J. and Gagnon, Joseph and Collins, Christopher G., 2021a, “Low Inflation Bends the Phillips Curve Around the World: Extended Results”, *Peterson Institute for International Economics Working Paper No. 21-15*.

Forbes, Kristin J. and Gagnon, Joseph and Collins, Christopher G., 2021b, “Pandemic inflation and nonlinear, global Phillips curves”, *Peterson Institute for International Economics Working Paper No. 21-15*, VoxEU.org, <https://voxeu.org/article/pandemic-inflation-and-nonlinear-global-phillips-curves>.

Gelos, Gaston and Yulia Ustyugova, 2017, “Inflation responses to commodity price shocks – How and why do countries differ?”, *Journal of International Money and Finance*, 72, 28-47.

Goodfriend, Marvin (1993), “Interest Rate Policy and the Inflation Scare Problem: 1979-1992,” *FRB Richmond Economic Quarterly* 79(1), 1-23.

Gopinath, Gita (2022), “How will the Pandemic and War Shape Future Monetary Policy?,” Speech delivered at the Jackson Hole Symposium, August 26.

Guerrieri, Luca and Matteo Iacoviello (2017), “Collateral constraints and macroeconomic asymmetries,” *Journal of Monetary Economics* 90(C), 28-49.

Gust, Christopher J., Edward P. Herbst, J. David López-Salido, and Matthew E. Smith (2017). “The Empirical Implications of the Interest-Rate Lower Bound,” *American Economic Review* 107(7), 1971-2006.

Harding, Martín, Jesper Lindé, and Mathias Trabandt (2022), “Resolving the missing deflation puzzle,” *Journal of Monetary Economics* 126(C), 15-34.

Hazell, J., J. Herreno, E. Nakamura, and J. Steinsson (2022), “The Slope of the Phillips Curve: Evidence from U.S. States,” *The Quarterly Journal of Economics*, 137, 1299– 1344.

Ilut, Cosmin, Rosen Valchev, and Nicolas Vincent (2020), “Paralyzed by fear: Rigid and discrete pricing under demand uncertainty,” *Econometrica* 88(5), 1899–1938.

- Juillard, Michel (1996), “Dynare : A Program for the Resolution and Simulation of Dynamic Models with Forward Variables Through the Use of a Relaxation Algorithm,” CEPREMAP Working Paper 9602.
- Kimball, M. S. (1995), “The Quantitative Analytics of the Basic Neomonetarist Model,” *Journal of Money, Credit, and Banking* 27(4), 1241–1277.
- Levin, Andrew, David López-Salido, and Tack Yun, (2007), “Strategic Complementarities and Optimal Monetary Policy”, CEPR Press Discussion Paper No. 6423.
- Levin, A., J. David López-Salido, Edward Nelson, Tack Yun, (2008), “Macroeconometric equivalence, microeconomic dissonance, and the design of monetary policy”, *Journal of Monetary Economics*, Volume 55, 2008, Pages S48-S62.
- L’Huillier, Jean-Paul and Gregory Phelan, (2023), “Can Supply Shocks Be Inflationary with a Flat Phillips Curve?”, *Manuscript*.
- Lindé, Jesper and Mathias Trabandt (2018), “Should We Use Linearized Models to Calculate Fiscal Multipliers?”, *Journal of Applied Econometrics* 33(7), 937–965.
- López-Salido, J. David and Francesca Loria, 2020. “Inflation at Risk,” Finance and Economics Discussion Series 2020-013, Board of Governors of the Federal Reserve System.
- Nakata, Taisuke (2017), “Uncertainty at the Zero Lower Bound,” *American Economic Journal: Macroeconomics* 9(3), 186-221.
- Phillips, A. W. (1958), “The Relationship between Unemployment and the Rate of Change of Money Wages in the United Kingdom 1861-1957,” *Economica* 25, 283–299.
- Smets, Frank and Raf Wouters (2007), “Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach”, *American Economic Review* 97(3), 586-606.
- Yun, Tack, (1996), “Nominal price rigidity, money supply endogeneity, and business cycles,” *Journal of Monetary Economics*, 37, issue 2-3, p. 345-370.

Appendix A The Smets and Wouters (2007) Model

This appendix contains the linearized and nonlinear equilibrium model equations of Smets and Wouters (2007). We describe the firms and households' problem in the model and state the market clearing conditions.^{A.1}

A.1 Firms and Price Setting

Final Goods Production The single final output good Y_t is produced using a continuum of differentiated intermediate goods $Y_t(f)$. Following Kimball (1995), the technology for transforming these intermediate goods into the final output good is

$$\int_0^1 G_Y \left(\frac{Y_t(f)}{Y_t} \right) df = 1. \quad (\text{A.1})$$

Following Dotsey and King (2005) and Levin, López-Salido and Yun (2007), we assume that $G_Y(\cdot)$ is given by a strictly concave and increasing function; its particular parameterization follows SW:

$$G_Y \left(\frac{Y_t(f)}{Y_t} \right) = \left(\frac{\phi_p}{1 - (\phi_p - 1)\epsilon_p} \left[\left(\frac{\phi_p + (1 - \phi_p)\epsilon_p}{\phi_p} \right) \frac{Y_t(f)}{Y_t} + \frac{(\phi_p - 1)\epsilon_p}{\phi_p} \right]^{\frac{1 - (\phi_p - 1)\epsilon_p}{\phi_p - (\phi_p - 1)\epsilon_p}} + \left[1 - \frac{\phi_p}{1 - (\phi_p - 1)\epsilon_p} \right] \right), \quad (\text{A.2})$$

where $\phi_p \geq 1$ denotes the gross markup of the intermediate firms. The parameter ϵ_p governs the degree of curvature of the intermediate firm's demand curve. When $\epsilon_p = 0$, the demand curve exhibits constant elasticity as with the standard Dixit-Stiglitz aggregator. When ϵ_p is positive—as in SW—this introduces more strategic complementarity in price setting, which causes intermediate firms to adjust prices less to a given change in marginal cost.

Firms that produce the final output good Y_t are perfectly competitive in both the product and the factor markets and take as given the price $P_t(f)$ of each intermediate good $Y_t(f)$.

^{A.1} For a description of the model that derives the log-linearized equations, we refer the reader to the appendix of the Smets and Wouters paper, which is available online at http://www.aeaweb.org/aer/data/june07/20041254_app.pdf.

They sell units of the final output good at a price P_t ; hence they solve the following problem:

$$\max_{\{Y_t, Y_t(f)\}} P_t Y_t - \int_0^1 P_t(f) Y_t(f) df, \quad (\text{A.3})$$

subject to the constraint (A.1).

Intermediate Goods Production A continuum of intermediate goods $Y_t(f)$ for $f \in [0, 1]$ is produced by monopolistically competitive firms, which utilize capital services $K_t(f)$ and a labor index $L_t(f)$ (defined below) to produce their respective output good. The form of the production function is Cobb-Douglas:

$$Y_t(f) = \varepsilon_t^a K_t(f)^\alpha [\gamma^t L_t(f)]^{1-\alpha} - \gamma^t \Phi, \quad (\text{A.4})$$

where γ^t represents the labor-augmenting deterministic growth rate in the economy, Φ denotes the fixed cost (which is related to the gross markup ϕ_p so that profits are zero in the steady-state), and ε_t^a is total factor productivity, which follows the process

$$\ln \varepsilon_t^a = (1 - \rho_a) \ln \varepsilon^a + \rho_a \ln \varepsilon_{t-1}^a + \eta_t^a, \eta_t^a \sim N(0, \sigma_a). \quad (\text{A.5})$$

Firms face perfectly competitive factor markets for renting capital at price R_{Kt} and hiring labor at a price given by the aggregate wage index W_t (defined below). As firms can costlessly adjust either factor of production, the standard static first-order conditions for cost minimization imply that all firms have identical marginal costs per unit of output.

The prices of the intermediate goods are determined by Calvo (1983)-Yun (1996)-style staggered nominal contracts. The probability $1 - \xi_p$ that any firm, f , receives a signal to reoptimize its price, $P_t(f)$, is assumed to be independent of the time that it last reset its price. If a firm is not allowed to optimize its price, it adjusts its price by a weighted combination of the lagged and steady-state rate of inflation, that is, $P_t(f) = (1 + \pi_{t-1})^{\iota_p} (1 + \pi)^{1-\iota_p} P_{t-1}(f)$, where $0 \leq \iota_p \leq 1$ and π_{t-1} denote net inflation in period $t - 1$, and π is the steady-state net inflation rate. A positive value of ι_p introduces structural inertia into the inflation process.

All told, this leads to the following optimization problem for the intermediate firms

$$\max_{\tilde{P}_t(f)} E_t \sum_{j=0}^{\infty} (\beta \xi_p)^j \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} \left[\tilde{P}_t(f) (\Pi_{s=1}^j (1 + \pi_{t+s-1})^{\iota_p} (1 + \pi)^{1-\iota_p}) - MC_{t+j} \right] Y_{t+j}(f), \quad (\text{A.6})$$

where $\tilde{P}_t(f)$ is the newly set price. Notice that with our assumptions, all firms that reoptimize their prices actually set the same price.

It would be ideal if the markup in (A.2) could be made stochastic and the model could be written in a recursive form. However, such an expression is not available and we, instead, directly introduce a shock, ε_t^p , in the first-order condition to the problem in (A.6). And following SW, we assume the shock is given by an exogenous ARMA(1,1) process:

$$\ln \varepsilon_t^p = (1 - \rho_p) \ln \varepsilon^p + \rho_p \ln \varepsilon_{t-1}^p + \eta_t^p - \mu_p \eta_{t-1}^p, \eta_t^p \sim N(0, \sigma_p). \quad (\text{A.7})$$

When this shock is introduced in the non-linear model, we put a scaling factor on it so that it enters a log-linearized representation of the model exactly the same way as the price-markup shock does in the SW model.

A.2 Households and Wage Setting

We assume a continuum of monopolistically competitive households (indexed on the unit interval), each of which supplies a differentiated labor service to the production sector; that is, goods-producing firms regard each household's labor services, $L_t(h)$, $h \in [0, 1]$, as imperfect substitutes for the labor services of other households. It is convenient to assume that a representative labor aggregator combines households' labor hours in the same proportions as firms would choose. Thus, the aggregator's demand for each household's labor is equal to the sum of the firms' labor demand. The aggregated labor index L_t has the following Kimball (1995) form:

$$L_t = \int_0^1 G_L \left(\frac{L_t(h)}{L_t} \right) dh = 1, \quad (\text{A.8})$$

where the function $G_L(\cdot)$ has the same functional form as (A.2) but is characterized by the corresponding parameters ϵ_w (governing convexity of labor demand by the aggregator) and ϕ_w (gross wage markup). The aggregator minimizes the cost of producing a given amount of the aggregate labor index, L_t , taking each household's wage rate, $W_t(h)$, as given, and then sells units of the labor index to the intermediate goods sector at unit cost W_t , which can naturally be interpreted as the aggregate wage rate.

The utility function of a typical member of household h is

$$\mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \left[\frac{1}{1-\sigma_c} (C_{t+j}(h) - \varkappa C_{t+j-1}) \right]^{1-\sigma_c} \exp \left(\frac{\sigma_c - 1}{1 + \sigma_l} L_{t+j}(h)^{1+\sigma_l} \right), \quad (\text{A.9})$$

where the discount factor β satisfies $0 < \beta < 1$. The period utility function depends on household h 's current consumption, $C_t(h)$, as well as the lagged aggregate per capita consumption, to allow for external habit persistence through the parameter $0 \leq \varkappa \leq 1$. The period utility function also depends inversely on hours worked, $L_t(h)$.

Household h 's budget constraint in period t states that its expenditure on goods and its net purchases of financial assets must equal its disposable income:

$$\begin{aligned} P_t C_t(h) + P_t I_t(h) + \frac{B_{t+1}(h)}{\varepsilon_t^b R_t} + \int_s \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h) \\ = B_t(h) + W_t(h) L_t(h) + R_t^k Z_t(h) K_t^p(h) - a(Z_t(h)) K_t^p(h) + \Gamma_t(h) - T_t(h). \end{aligned} \quad (\text{A.10})$$

Thus, the household purchases part of the final output good (at price P_t), which it chooses either to consume $C_t(h)$ or to invest $I_t(h)$ in physical capital. Following Christiano, Eichenbaum, and Evans (2005), investment augments the household's (end-of-period) physical capital stock, $K_{t+1}^p(h)$, according to

$$K_{t+1}^p(h) = (1 - \delta) K_t^p(h) + \varepsilon_t^i \left[1 - S \left(\frac{I_t(h)}{I_{t-1}(h)} \right) \right] I_t(h). \quad (\text{A.11})$$

The extent to which investment by each household h turns into physical capital is assumed to depend on an exogenous shock, ε_t^i , and how rapidly the household changes its rate of

investment according to the function $S\left(\frac{I_t(h)}{I_{t-1}(h)}\right)$, which we specify as

$$S(x_t) = \frac{\varphi}{2} (x_t - \gamma)^2. \quad (\text{A.12})$$

Notice that this function satisfies $S(\gamma) = 0$, $S'(\gamma) = 0$ and $S''(\gamma) = \varphi$. The stationary investment-specific shock ε_t^i follows

$$\ln \varepsilon_t^i = \rho_i \ln \varepsilon_{t-1}^i + \eta_t^i, \eta_t^i \sim N(0, \sigma_i). \quad (\text{A.13})$$

In addition to accumulating physical capital, households may augment their financial assets through increasing their government nominal bond holdings, (B_{t+1}) , from which they earn an interest rate of R_t . The return on these bonds is also subject to a risk shock, ε_t^b , which follows

$$\ln \varepsilon_t^b = \rho_b \ln \varepsilon_{t-1}^b + \eta_t^b, \eta_t^b \sim N(0, \sigma_b). \quad (\text{A.14})$$

Agents can engage in frictionless trading of a complete set of contingent claims to diversify away idiosyncratic risk. The term $\int_s \xi_{t,t+1} B_{D,t+1}(h) - B_{D,t}(h)$ represents net purchases of these state-contingent domestic bonds, with $\xi_{t,t+1}$ denoting the state-dependent price, and $B_{D,t+1}(h)$ the quantity of such claims purchased at time t .

On the income side, each member of household h earns after-tax labor income of $W_t(h) L_t(h)$ and after-tax capital rental income of $R_t^k Z_t(h) K_t^p(h)$ and pays a utilization cost of the physical capital equal to $a(Z_t(h)) K_t^p(h)$, where $Z_t(h)$ is the capital utilization rate, so that the capital services provided by household h , $K_t(h)$, equal $Z_t(h) K_t^p(h)$. The capital utilization adjustment function, $a(Z_t(h))$, is assumed to be given by

$$a(Z_t(h)) = \frac{r^k}{\tilde{z}_1} [\exp(\tilde{z}_1 (Z_t(h) - 1)) - 1], \quad (\text{A.15})$$

where r^k is the steady-state net real interest rate (\bar{R}_t^K / \bar{P}_t). Notice that the adjustment function satisfies $a(1) = 0$, $a'(1) = r^k$, and $a''(1) \equiv r^k \tilde{z}_1$. Following SW, we want to write $a''(1) = z_1 = \psi / (1 - \psi) > 0$, where $\psi \in [0, 1)$ and a higher value of ψ implies a higher cost of changing the utilization rate. Our parameterization of the adjustment cost function then

implies that we need to set $\tilde{z}_1 \equiv z_1/r^k$. Finally, each member also receives an aliquot share amount to $\Gamma_t(h)$ of the profits of all firms and pays a lump-sum tax of $T_t(h)$ (regarded as taxes net of any transfers).

In every period t , each member of household h maximizes the utility function (A.9) with respect to its consumption, investment, (end-of-period) physical capital stock, capital utilization rate, bond holdings, and holdings of contingent claims, subject to its labor demand function, budget constraint (A.10), and transition equation for capital (A.11).

Households also set nominal wages in Calvo (1983)-style staggered contracts that are generally similar to the price contracts described previously. Thus, the probability that a household receives a signal to reoptimize its wage contract in a given period is denoted by $1 - \xi_w$. In addition, SW specify the following dynamic indexation scheme for the adjustment of the wages of those households that do not receive a signal to reoptimize: $W_t(h) = \gamma (1 + \pi_{t-1})^{\iota_w} (1 + \pi)^{1-\iota_w} W_{t-1}(h)$. All told, this leads to the following optimization problem for the households:

$$\max_{\tilde{W}_t(h)} E_t \sum_{j=0}^{\infty} (\beta \xi_w)^j \frac{\Xi_{t+j} P_t}{\Xi_t P_{t+j}} \left[\tilde{W}_t(h) \left(\prod_{s=1}^j \gamma (1 + \pi_{t+s-1})^{\iota_w} (1 + \pi)^{1-\iota_w} \right) - W_{t+j} \right] L_{t+j}(h), \quad (\text{A.16})$$

where $\tilde{W}_t(h)$ is the newly set wage. Notice that with our assumptions all households that reoptimize their wages will actually set the same wage.

Following the same approach as with the intermediate-goods firms, we introduce a shock, ε_t^w , in the resulting first-order condition. This shock, following SW, is assumed to be given by an exogenous ARMA(1,1) process:

$$\ln \varepsilon_t^w = (1 - \rho_w) \ln \varepsilon^w + \rho_w \ln \varepsilon_{t-1}^w + \eta_t^w - \mu_w \eta_{t-1}^w, \eta_t^w \sim N(0, \sigma_w). \quad (\text{A.17})$$

As discussed previously, we use a scaling factor for this shock so that it enters into the log-linearized representation of the model in exactly the same way as the wage-markup shock in SW.

A.3 Monetary Policy

The monetary authority follows a Taylor rule in adjusting the interest rate in response to changes in inflation and the output gap. An important difference with respect to the standard SW model is that we consider a nonlinear policy rule to explicitly take the ZLB into account:

$$R_t = \max \left[1 + \bar{b}, R_{t-1}^{\rho_R} \bar{R}^{(1-\rho_R)} \left(\frac{\pi_t}{\bar{\pi}} \right)^{(r_\pi)(1-\rho_R)} \left(\frac{y_t}{y_t^{pot}} \right)^{(r_y)(1-\rho_R)} \left(\frac{y_t/y_t^{pot}}{y_{t-1}/y_{t-1}^{pot}} \right)^{r_{\Delta y}} \varepsilon_{r,t} \right], \quad (\text{A.18})$$

where $\bar{b} > 0$ is a constant reflecting the level of the effective lower bound (ELB). Since the federal funds rate never reached exactly zero but oscillated around 10 (annualized) basis points throughout the ELB period, we set \bar{b} equal to 10 (annualized) basis points. y_t^{pot} is the output prevailing in the flexible price and wage economy in absence of the inefficient monetary policy, and price- and wage-markup shocks.

A.4 Market Clearing Conditions

Government purchases, G_t , are exogenous, and the process for government spending relative to trend output, that is, $g_t = G_t/(\gamma^t Y)$, is given by the following exogenous AR(1) process:

$$\ln g_t = (1 - \rho_g) \ln g + \rho_g (\ln g_{t-1} - \rho_{ga} \ln \varepsilon_{t-1}^a) + \varepsilon_t^g, \varepsilon_t^g \sim N(0, \sigma_g). \quad (\text{A.19})$$

Government purchases have no effect on the marginal utility of private consumption, nor do they serve as an input into goods production. Moreover, the government is assumed to balance its budget through lump-sum taxes (which are irrelevant, since Ricardian equivalence holds in the model).

Total output of the final goods sector is used as follows:

$$Y_t = C_t + I_t + G_t + a(Z_t) \bar{K}_t, \quad (\text{A.20})$$

where $a(Z_t) \bar{K}_t$ is the capital utilization adjustment cost.

Finally, one can derive an aggregate production constraint, which depends on aggregate technology, capital, labor, and fixed costs, as well as the price and wage dispersion terms.^{A.2}

A.5 Model Parameterization

When solving the model, we consider two alternative parameterizations. First, we adopt the parameter estimates (posterior mode) in Table A.1 of SW. Second, we re-estimate the SW model setting a lower mean and standard deviation for the steady-state price-markup (ϕ_p) prior and a higher value for the curvature of the intermediate firm's demand curve (ϵ_p). Specifically, we consider a prior $\phi_p \sim N(1.2, 0.05)$, compared to the SW prior of $\phi_p \sim N(1.25, 0.125)$, and we estimate $\epsilon_p = 64.5$ instead of it being set to 10 as in SW. In both cases we use the same values as SW for the calibrated parameters. Table A.1. provides the values of SW's baseline estimation and Table A.2. provides the parameter values with prior $\phi_p \sim N(1.2, 0.05)$ and $\epsilon_p = 64.5$.

^{A.2} We refer the interested reader to Adjemian, Paries and Moyen (2008) for further details.

Table A.1: Parameter values in Smets and Wouters (2007).

Panel A: Calibrated					
Parameter	Description	Value	Parameter	Description	Value
δ	Depreciation rate	0.025	ϵ_p	Kimball Elast. GM	10
ϕ_w	Gross wage markup	1.50	ϵ_w	Kimball Elast. LM	10
g_y	Gov't G/Y ss-ratio	0.18			
Panel B: Estimated					
Parameter	Description	Value	Parameter	Description	Value
φ	Investment adj. cost	5.48	ϕ_p	Gross price markup	1.61
σ_c	Inv. subs. elast. of cons.	1.39	γ	Steady-state gross growth	1.0043
\varkappa	Degree of ext. habit	0.71	\bar{l}	Steady-state hours worked	0.25
ξ_w	Calvo prob. wages	0.73	π	Steady-state net infl. rate	0.0081
σ_l	Labor supply elas.	1.92	β	Discount factor	0.9984
ξ_p	Calvo prob. prices	0.65	ρ_R	Taylor rule, int. rate smooth.	0.81
ι_w	Ind. for non-opt. wages	0.59	$r_{\Delta y}$	Taylor rule, coef. Δ out. gap	0.22
ι_p	Ind. for non-opt. prices	0.22	r_y	Taylor rule, coef. out. gap	0.08
α	Capital production share	0.19	r_π	Taylor rule, coef. inflation	2.03
ψ	Capital utilization cost	0.54			
Panel C: Shock Processes					
Shock	Persistence	MA(1)	Std. of Innovation (%)		
Neutral technology	ρ_a 0.95	-	σ_a		0.45
Risk premium	ρ_b 0.18	-	σ_b		0.24
Gov't spending	ρ_g 0.97	ρ_{ga} 0.52	σ_g		0.52
Inv. specific tech.	ρ_i 0.71		σ_i		0.45
Price markup	ρ_p 0.90	μ_p 0.74	σ_p		0.14
Wage markup	ρ_w 0.97	μ_w 0.88	σ_w		0.24
Monetary policy	ρ_r 0.2	-	σ_r		0.24

Table A.2: Parameter Values with prior $\phi_p \sim N(1.2, 0.05)$ and estimated ϵ_p .

Panel A: Calibrated					
Parameter	Description	Value	Parameter	Description	Value
δ	Depreciation rate	0.025	ξ_p	Calvo prob. prices	0.67
ϕ_w	Gross wage markup	1.50	ϵ_w	Kimball Elast. LM	10
g_y	Gov't G/Y ss-ratio	0.18			
Panel B: Estimated					
Parameter	Description	Value	Parameter	Description	Value
φ	Investment adj. cost	5.58	ϕ_p	Gross price markup	1.34
σ_c	Inv. subs. elast. of cons.	1.41	γ	Steady-state gross growth	1.0044
\varkappa	Degree of ext. habit	0.68	\bar{l}	Steady-state hours worked	—
ξ_w	Calvo prob. wages	0.80	π	Steady-state net infl. rate	0.0087
σ_l	Labor supply elas.	2.20	β	Discount factor	0.9987
ϵ_p	Kimball elast. GM	64.5	ρ_R	Taylor rule, int. rate smooth.	0.82
ι_w	Ind. for non-opt. wages	0.56	$r_{\Delta y}$	Taylor rule, coef. Δ out. gap	0.25
ι_p	Ind. for non-opt. prices	0.24	r_y	Taylor rule, coef. out. gap	0.097
α	Capital production share	0.18	r_π	Taylor rule, coef. inflation	1.93
ψ	Capital utilization cost	0.49			
Panel C: Shock Processes					
Shock	Persistence	MA(1)	Std. of Innovation (%)		
Neutral technology	ρ_a 0.95	-	σ_a		0.48
Risk premium	ρ_b 0.22	-	σ_b		0.23
Gov't spending	ρ_g 0.97	ρ_{ga} 0.53	σ_g		0.47
Inv. specific tech.	ρ_i 0.70		σ_i		0.40
Price markup	ρ_p 0.83	μ_p 0.69	σ_p		0.13
Wage markup	ρ_w 0.97	μ_w 0.93	σ_w		0.28
Monetary policy	ρ_r 0.11	-	σ_r		0.23

Note that we adapt and rescale the processes of the price- and wage-markup shocks so that when our model is log-linearized it exactly matches the original SW model.

A.6 Summary of Nonlinear Model Equations

We detrend the variables with a deterministic trend, γ , and the nominal variables are replaced by their real counterparts. For instance, we use the following definitions:

$$\begin{aligned}
 k_t &= \frac{K_t}{\gamma^t}; w_t = \frac{W_t}{P_t \gamma^t}; w_t^* = \frac{W_t^*}{P_t \gamma^t} \\
 r_t^k &= \frac{R_t^k}{P_t}; mc_t = \frac{MC_t}{P_t}; p_t^* = \frac{P_t^*}{P_t}; \delta_t^w = \frac{\Lambda_t^w}{P_t \gamma^t}, \delta_t^p = \frac{\Lambda_t^p}{P_t} \\
 \xi_t &\equiv \Xi_t \gamma^{\sigma c t} \\
 \gamma_{1,t}^p &= \frac{\Gamma_{1,t}^p}{\gamma^t}, \gamma_{2,t}^p = \frac{\Gamma_{2,t}^p}{\gamma^t}, \gamma_{3,t}^p = \frac{\Gamma_{3,t}^p}{\gamma^t}, \\
 \gamma_{1,t}^w &= \frac{\Gamma_{1,t}^w}{(\gamma^t)^{\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}}}, \gamma_{2,t}^w = \frac{\Gamma_{2,t}^w}{(\gamma^t)^{1+\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}}},
 \end{aligned}$$

Also, we define $g_t \equiv G_t/Y_t$ and re-define the fixed cost $\Phi \equiv (\phi_p - 1) y$, where y is the steady-state level of output.

Market clearing

$$c_t + i_t + g_t y + a(U_t) \frac{k_{t-1}^h}{\gamma} = y_t \quad (\text{A.1})$$

$$y_t \frac{\epsilon_p + s_t^p}{1 + \epsilon_p} = (\varepsilon_t^a (k_t^s)^\alpha L_t^{1-\alpha} - (\phi_p - 1) y) \quad (\text{A.2})$$

$$k_t^s = \frac{1}{\gamma} U_t k_{t-1}^h \quad (\text{A.3})$$

$$k_t^h = \frac{1 - \delta}{\gamma} k_{t-1}^h + \varepsilon_t^i \left[1 - S \left(\frac{i_t \gamma}{i_{t-1}} \right) \right] i_t \quad (\text{A.4})$$

$$s_t^p = (1 - \xi_p) \left(\frac{p_t^*}{\delta_t^p} \right)^{-\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} + \xi_p \left(\frac{\pi^{1-\iota_p} \pi_{t-1}^{\iota_p} \delta_{t-1}^p}{\pi_t \delta_t^p} \right)^{-\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} s_{t-1}^p \quad (\text{A.5})$$

$$s_t^w = (1 - \xi_w) \left(\frac{w_t^*}{\delta_t^w} \right)^{-\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}} + \xi_w \left(\frac{\pi^{1-\iota_w} \pi_{t-1}^{\iota_w} \delta_{t-1}^w}{\pi_t \delta_t^w} \right)^{-\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}} s_{t-1}^w \quad (\text{A.6})$$

$$1 = (1 - \xi_p) \left(\frac{p_t^*}{\delta_t^p} \right)^{-\frac{1+\phi_p \epsilon_p}{\phi_p - 1}} + \xi_p \left(\frac{\pi^{1-\iota_p} \pi_{t-1}^{\iota_p} \delta_{t-1}^p}{\pi_t \delta_t^p} \right)^{-\frac{1+\phi_p \epsilon_p}{\phi_p - 1}} \quad (\text{A.7})$$

$$1 = (1 - \xi_w) \left(\frac{w_t^*}{\delta_t^w} \right)^{-\frac{1+\phi_w \epsilon_w}{\phi_w - 1}} + \xi_w \left(\frac{\pi^{1-\iota_w} \pi_{t-1}^{\iota_w} \delta_{t-1}^w}{\pi_t \delta_t^w} \right)^{-\frac{1+\phi_w \epsilon_w}{\phi_w - 1}} \quad (\text{A.8})$$

$$(1 + \epsilon_w) w_t = (1 + \epsilon_w s_t^{wl}) \delta_t^w \quad (\text{A.9})$$

$$(1 + \epsilon_p) = (1 + \epsilon_p s_t^{pl}) \delta_t^p \quad (\text{A.10})$$

$$s_t^{pl} = (1 - \xi_p) \left(\frac{p_t^*}{\delta_t^p} \right) + \xi_p \left(\frac{\pi^{1-\iota_p} \pi_{t-1}^{\iota_p} \delta_{t-1}^p}{\pi_t \delta_t^p} \right) s_{t-1}^{pl} \quad (\text{A.11})$$

$$s_t^{wl} = (1 - \xi_w) \left(\frac{w_t^*}{\delta_t^w} \right) + \xi_w \left(\frac{\pi^{1-\iota_w} \pi_{t-1}^{\iota_w} \delta_{t-1}^w}{\pi_t \delta_t^w} \right) s_{t-1}^{wl} \quad (\text{A.12})$$

Firms

$$\frac{k_t^s}{L_t} = \frac{\alpha}{1 - \alpha} \frac{w_t}{r_t^k} \quad (\text{A.13})$$

$$mc_t = \left(\frac{\alpha}{1 - \alpha} \frac{w_t}{r_t^k} \right)^{-\alpha} \frac{w_t}{(1 - \alpha) \varepsilon_t^a} \quad (\text{A.14})$$

Households

$$\xi_t \equiv \Xi_t \gamma^{\sigma_c t} = \varepsilon_t^d \left(c_t - \frac{\chi}{\gamma} c_{t-1} \right)^{-\sigma_c} \exp \left((\sigma_c - 1) \frac{(L_t^h)^{1+\sigma_l}}{1 + \sigma_l} \right); \quad L_t^h \equiv L_t \frac{\epsilon_w + s_t^w}{1 + \epsilon_w} \quad (\text{A.15})$$

$$1 = Q_t \varepsilon_t^i \left[1 - S \left(\frac{i_t \gamma}{i_{t-1}} \right) - S' \left(\frac{i_t \gamma}{i_{t-1}} \right) \frac{i_t \gamma}{i_{t-1}} \right] + \beta \gamma^{-\sigma} E_t \frac{\xi_{t+1}}{\xi_t} Q_{t+1} \varepsilon_{t+1}^i S' \left(\frac{i_{t+1} \gamma}{i_t} \right) \left(\frac{i_{t+1} \gamma}{i_t} \right)^2 \quad (\text{A.16})$$

$$R_t^{-1} = \varepsilon_t^b \beta \gamma^{-\sigma} E_t \frac{\xi_{t+1}}{\xi_t} \Pi_{t+1}^{-1} \quad (\text{A.17})$$

$$Q_t = \beta \gamma^{-\sigma} E_t \frac{\xi_{t+1}}{\xi_t} \left[(1 - \delta) Q_{t+1} + (r_{t+1}^k U_{t+1} - a(U_{t+1})) \right] \quad (\text{A.18})$$

$$r_t^k \equiv \frac{R_t^k}{P_t} = a'(U_t) \quad (\text{A.19})$$

Wage Setting

$$\frac{1 + \phi_w \epsilon_w}{1 + \epsilon_w} w_t^* \gamma_{1,t}^w = \phi_w \gamma_{2,t}^w + \frac{\epsilon_w (\phi_w - 1)}{1 + \epsilon_w} (w_t^*)^{\frac{\phi_w(1+\epsilon_w)}{\phi_w-1} + 1} \gamma_{3,t}^w \quad (\text{A.20})$$

$$\gamma_{1,t}^w = (\delta_t^w)^{\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}} L_t + (\beta \gamma^{1-\sigma}) \xi_w E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_w} \pi_t^{\iota_w}}{\pi_{t+1}} \right)^{-\frac{1+\phi_w \epsilon_w}{\phi_w-1}} \gamma_{1,t+1}^w \quad (\text{A.21})$$

$$\gamma_{2,t}^w = (\delta_t^w)^{\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}} w_t^h \varepsilon_t^w L_t + (\beta \gamma^{1-\sigma}) \xi_w E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_w} \pi_t^{\iota_w}}{\pi_{t+1}} \right)^{-\frac{\phi_w(1+\epsilon_w)}{\phi_w-1}} \gamma_{2,t+1}^w \quad (\text{A.22})$$

$$\gamma_{3,t}^w = L_t + (\beta \gamma^{1-\sigma}) \xi_w E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_w} \pi_t^{\iota_w}}{\pi_{t+1}} \right) \gamma_{3,t+1}^w \quad (\text{A.23})$$

Price Setting

$$\frac{1 + \phi_p \epsilon_p}{1 + \epsilon_p} p_t^* \gamma_{1,t}^p = \phi_p \gamma_{2,t}^p + \frac{\epsilon_p (\phi_p - 1)}{1 + \epsilon_p} (p_t^*)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1} + 1} \gamma_{3,t}^p, \quad (\text{A.24})$$

$$\gamma_{1,t}^p = (\delta_t^p)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right)^{-\frac{1+\phi_p \epsilon_p}{\phi_p-1}} \gamma_{1,t+1}^p, \quad (\text{A.25})$$

$$\gamma_{2,t}^p = (\delta_t^p)^{\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} mc_t \varepsilon_{p,t} y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right)^{-\frac{\phi_p(1+\epsilon_p)}{\phi_p-1}} \gamma_{2,t+1}^p, \quad (\text{A.26})$$

$$\gamma_{3,t}^p = y_t + (\beta \gamma^{1-\sigma}) \xi_p E_t \frac{\xi_{t+1}}{\xi_t} \left(\frac{\pi^{1-\iota_p} \pi_t^{\iota_p}}{\pi_{t+1}} \right) \gamma_{3,t+1}^p, \quad (\text{A.27})$$

Monetary Policy

$$R_t = \max \left[1 + \bar{b}, R_{t-1}^{\rho_R} \bar{R}^{(1-\rho_R)} \left(\frac{\pi_t}{\pi} \right)^{r_\pi(1-\rho_R)} \left(\frac{y_t}{y_t^{pot}} \right)^{r_y(1-\rho_R)} \left(\frac{y_t/y_t^{pot}}{y_{t-1}/y_{t-1}^{pot}} \right)^{r_{\Delta y}} \varepsilon_{r,t} \right] \quad (\text{A.28})$$

Together, this constitutes an equation system with 28 equations and the following 28 endogenous variables: $c_t, y_t, L_t, i_t, k_t^s, k_t^h, U_t, p_t^*, w_t^*, \pi_t, s_t^p, s_t^w, \delta_t^p, \delta_t^w, s_t^{pl}, s_t^{wl}, r_t^k, w_t, mc_t, \xi_t, R_t, Q_t, \gamma_{1,t}^p, \gamma_{2,t}^p, \gamma_{3,t}^p, \gamma_{1,t}^w, \gamma_{2,t}^w, \gamma_{3,t}^w$.

The flexible price and wage allocations are obtained by setting $\xi_p = \xi_w = 0$ which defines

y_t^{pot} . Only four shocks affect the flex price-wage allocations; $\varepsilon_t^a, \varepsilon_t^b, \varepsilon_t^i$, and g_t .

A.7 Summary of Linearized Model Equations

In this section, we summarize the log-linear equations of the SW model. The complete model also includes the seven exogenous shocks $\varepsilon_t^a, \varepsilon_t^b, \varepsilon_t^i, \varepsilon_t^p, \varepsilon_t^w, \varepsilon_t^r$, and g_t , but their processes are not stated here as they were presented earlier. Consistent with the notation of the log-linearized *endogenous* variables $\hat{x}_t = dx_t/x$, the exogenous shocks are denoted with a ‘hat’, i.e., $\hat{\varepsilon}_t = \ln \varepsilon_t$.

First, we have the consumption Euler equation:

$$\hat{c}_t = \frac{1}{(1+\varkappa/\gamma)} \mathbb{E}_t \hat{c}_{t+1} + \frac{\varkappa/\gamma}{(1+\varkappa/\gamma)} \hat{c}_{t-1} - \frac{1-\varkappa/\gamma}{\sigma_c(1+\varkappa/\gamma)} (\hat{R}_t - \mathbb{E}_t \hat{\pi}_{t+1} + \hat{\varepsilon}_t^b) - \frac{(\sigma_c-1)(w_*^h L/c_*)}{\sigma_c(1+\varkappa/\gamma)} (\mathbb{E}_t \hat{L}_{t+1} - \hat{L}_t), \quad (\text{A.29})$$

where \varkappa is the external habit parameter, σ_c is the reciprocal of the intertemporal substitution elasticity, and $w_*^h L/c_*$ is the steady-state nominal labor earnings to consumption ratio.

Next, we have the investment Euler equation:

$$\hat{i}_t = \frac{1}{(1+\bar{\beta}\gamma)} \left(\hat{i}_{t-1} + \bar{\beta}\gamma \mathbb{E}_t \hat{i}_{t+1} + \frac{1}{\gamma^2 \varphi} \hat{Q}_t^k \right) + \hat{\varepsilon}_t^q, \quad (\text{A.30})$$

where $\bar{\beta} = \beta\gamma^{-\sigma_c}$, φ is the investment adjustment cost, and the investment-specific technology shock $\hat{\varepsilon}_t^q$ has been rescaled so that it enters linearly with a unit coefficient. Additionally $i_1 = 1/(1+\beta)$ and $i_2 = i_1/\psi$, where β is the discount factor and ψ is the elasticity of the capital adjustment cost function.

The price of capital is determined by

$$\hat{Q}_t^k = -(\hat{R}_t - \mathbb{E}_t \hat{\pi}_{t+1} + \hat{\varepsilon}_t^b) + q_1 \mathbb{E}_t r_{t+1}^k + (1 - q_1) \mathbb{E}_t Q_{t+1}^k, \quad (\text{A.31})$$

where $q_1 \equiv r_*^k / (r_*^k + (1 - \delta))$, in which r_*^k is the steady-state rental rate to capital and δ is the depreciation rate.

Fourth, we have the optimal condition for the capital utilization rate \widehat{u}_t :

$$\widehat{u}_t = (1 - \psi) / \psi \widehat{r}_t^k, \quad (\text{A.32})$$

where ψ is the elasticity of the capital utilization cost function and the capital services used in production (\widehat{k}_t) is defined as

$$\widehat{k}_t = \widehat{u}_t + \widehat{k}_{t-1}, \quad (\text{A.33})$$

where \widehat{k}_{t-1} is the physical capital stock, which evolves according to the following capital accumulation equation:

$$\widehat{k}_t = \kappa_1 \widehat{k}_{t-1} + (1 - \kappa_1) \widehat{i}_t + \kappa_2 \widehat{\varepsilon}_t^q \quad (\text{A.34})$$

with $\kappa_1 = 1 - (i_*/\bar{k}_*)$ and $\kappa_2 = (i_*/\bar{k}_*)\gamma^2\varphi(1 + \bar{\beta}\gamma)$.

The following optimal capital/labor input condition also holds:

$$\widehat{k}_t = \widehat{w}_t - \widehat{r}_t^k + \widehat{L}_t, \quad (\text{A.35})$$

where \widehat{w}_t is the real wage.

The log-linearized production function is given by

$$\widehat{y}_t = \phi_p (\alpha \widehat{k}_t + (1 - \alpha) \widehat{L}_t + \widehat{\varepsilon}_t^a), \quad (\text{A.36})$$

in which ϕ_p is the fixed cost of production corresponding to the gross price markup in the steady-state, and $\widehat{\varepsilon}_t^a$ is the exogenous TFP process.

Aggregate demand must equal aggregate supply:

$$\widehat{y}_t = \frac{c_*}{y_*} \widehat{c}_t + \frac{i_*}{y_*} \widehat{i}_t + g_t + \frac{r^k k_*}{y_*} \widehat{u}_t, \quad (\text{A.37})$$

where g_t represents the exogenous demand component.

Next, we have the following log-linearized price setting equation with dynamic indexation ι_p :

$$\widehat{\pi}_t - \iota_p \widehat{\pi}_{t-1} = \pi_1 (E_t \widehat{\pi}_{t+1} - \iota_p \widehat{\pi}_t) - \pi_2 \widehat{\mu}_t^p + \widehat{\varepsilon}_t^p, \quad (\text{A.38})$$

where $\pi_1 = \beta$, $\pi_2 = (1 - \xi_p \beta)(1 - \xi_p) / [\xi_p(1 + (\phi_p - 1)\epsilon_p)]$, $1 - \xi_p$ is the probability of each firm being able to reoptimize the price each period, ϵ_p is the curvature of the aggregator function (eq. (A.1)), and the markup shock $\hat{\varepsilon}_t^p$ has been rescaled to enter with a unit coefficient. The price markup, $\hat{\mu}_t^p$, equals the inverse of the real marginal cost, $\hat{\mu}_t^p = -\hat{m}c_t$, which in turn is given by

$$\hat{m}c_t = (1 - \alpha) \hat{w}_t^{real} + \alpha \hat{r}_t^k - \hat{\varepsilon}_t^a. \quad (\text{A.39})$$

We also have the following wage-setting equation, allowing for dynamic indexation of wages for non-optimizing households:

$$(1 + \bar{\beta}\gamma)\hat{w}_t^{real} - \hat{w}_{t-1}^{real} - \bar{\beta}\gamma E_t \hat{w}_{t+1}^{real} = \frac{(1 - \xi_w \bar{\beta}\gamma)(1 - \xi_w)}{[\xi_w(1 + (\phi_w - 1)\epsilon_w)]} \left(\frac{1}{1 - \varkappa/\gamma} \hat{c}_t - \frac{\varkappa/\gamma}{1 - \varkappa/\gamma} \hat{c}_{t-1} + \sigma_l \hat{L}_t - \hat{w}_t \right) - (1 + \bar{\beta}\gamma \iota_w) \hat{\pi}_t + \iota_w \hat{\pi}_{t-1} + \bar{\beta}\gamma E_t \hat{\pi}_{t+1} + \hat{\varepsilon}_t^w, \quad (\text{A.40})$$

where ϕ_w is the gross wage markup, $1 - \xi_p$ is the probability of each household being able to reoptimize its wage each period, ϵ_w is the curvature of the aggregator function (eq. A.8), and σ_l determines the elasticity of labor supply, given σ_c (see equation (A.9)). The exogenous wage-markup shock $\hat{\varepsilon}_t^w$ has been rescaled to enter linearly with a unit coefficient.

Finally, we have the following monetary policy rule:

$$\hat{R}_t = \rho_R \hat{R}_{t-1} + (1 - \rho_R) (r_\pi \hat{\pi}_t + r_y \hat{y}_t^{gap}) + r_{\Delta y} \Delta \hat{y}_t^{gap} + \hat{\varepsilon}_t^r, \quad (\text{A.41})$$

where $\hat{y}_t^{gap} = \hat{y}_t - \hat{y}_t^{pot}$, or in other words, the difference between the actual output and the output prevailing in the flexible price and wage economy in absence of the inefficient price- and wage-markup shocks. We solve for \hat{y}_t^{pot} by setting $\xi_p = \xi_w = 0$ (or arbitrarily close to nil) and removing $\hat{\varepsilon}_t^w$ and $\hat{\varepsilon}_t^p$ from the system of equations given by (A.29) – (A.41). When linearizing the model, we do not take the ZLB into account and the policy rate equals the shadow rate implied by the Taylor rule in equation (A.41) at all times.

A.8 Observer Equations and Data

We have the following observer equations in the nonlinear model:

$$\begin{aligned}\pi_t^{obs} &= 100 \ln \pi_t \\ \Delta w_t^{obs} &= 100 \ln w_t/w_{t-1} + \gamma \\ R_t^{obs} &= 100 (R_t - 1) \\ \Delta y_t^{obs} &= 100 \ln y_t/y_{t-1} + \gamma \\ \Delta c_t^{obs} &= 100 \ln c_t/c_{t-1} + \gamma \\ \Delta i_t^{obs} &= 100 \ln i_t/i_{t-1} + \gamma \\ l_t^{obs} &= 100 \ln l_t/l\end{aligned}$$

We use the same data as Smets and Wouters (2007), except that we update their dataset through 2014Q2.