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ABSTRACT

We study the implications of increased price flexibility on output volatility. In a simple DSGE model, we show analytically that more flexible prices always amplify output volatility for supply shocks and also amplify output volatility for demand shocks if monetary policy does not respond strongly to inflation. More flexible prices often reduce welfare, even under optimal monetary policy if full efficiency cannot be attained. We estimate a medium-scale DSGE model using post-WWII U.S. data. In a counterfactual experiment we find that if prices and wages are fully flexible, the standard deviation of annualized output growth more than doubles.

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1 Introduction

How sticky are nominal prices? In recent years we have seen an explosion in empirical research addressing this question using micro-data (see for example, Bils and Klenow (2004), Gopinath and Rigobon (2008), Klenow and Kryvtsov (2008), and Nakamura and Steinsson (2008)). Answers have ranged from prices adjusting once every five months on average to more than one year.¹ From a theoretical perspective, the primary motivation behind such work, either implicitly or explicitly, appears to be to settle the following question: Can monetary policy actions lead to large and persistent movements in output? Researchers seem to have in mind that modeling sticky prices is important if prices adjust infrequently in the data, while not if they adjust all the time. The first case corresponds to a “Keynesian economy” in which prices adjust only infrequently, and thus monetary policy and nominal frictions matter for real outcomes. The second case corresponds to a perfectly “classical economy” in which prices adjust at all times, and thus monetary policy and pricing frictions play little or no role in stabilizing or destabilizing the business cycle. The degree to which one view is correct, then, is presumably determined by the degree to which a “flexible” or “fixed” pricing strategy of firms is closer to reality.

For a casual reader of this recent empirical literature, then, the question posed by this paper may strike as odd: Can increasing price flexibility be destabilizing for output? It might seem obvious that more flexible prices make monetary frictions as given by rigid prices – and more specifically monetary policy – play little or no role in stabilizing or destabilizing the business cycle. We will argue however, that not only is that conclusion not obvious, but in fact, one can easily make the opposite case, both in theory and in an estimated model.

Moreover, the question – whose answer is sometimes taken as being self-evident – is in fact an old and classic question in macroeconomics and one that we argue remains unsettled. To make this clear we have stolen the title from De Long and Summers (1986), a paper published 25 years ago. They use a dynamic IS-LM model with rational expectations and Taylor-type wage contracts to show that an increase in flexibility can increase output volatility for reasons we make clear shortly. But this argument goes even farther back as these authors point out. A similar observation is made, for example, by Tobin (1975) using a more old-style Keynesian model. Similarly, Keynes (1936) declared that “it would be much better that wages should be rigidly fixed and deemed incapable of material changes, than the depression should be accompanied by a gradual downward tendency of money-wages”

¹For a survey of this literature, see Klenow and Malin (2010).

using more informal arguments. In fact, the question about the relationship between price flexibility and output volatility even pre-dates Keynes. As early as 1923, Fisher (1923, 1925) saw the business cycle as “largely a dance of the dollar:” According to Fisher, expected deflation leads to high anticipated real interest rates that suppresses investment and output.

In this paper we address this classic question in macroeconomics in a modern micro-founded DSGE model with infrequent price adjustment. Our analysis proceeds in two steps. We first analyze a simplified model, basically the prototypical three-equation New Keynesian model, where we can show several key results in closed form and are able to characterize explicitly the conditions under which higher price flexibility, given by an increase in the frequency of price adjustment by firms, can be destabilizing and vice versa. We consider several extensions to this exercise, such as analyzing effects not just on output volatility but also on welfare, exploring several variants of the interest rate reaction function, studying the role of wage rigidities, and considering optimal monetary policy. We then move on to a quantitative medium scale model with a rich set of nominal and real rigidities popularized by Smets and Wouters (2007), building on Rotemberg and Woodford (1997) and Christiano et al. (2005). We estimate this model using Bayesian methods and then ask the following question: Taking the various structural shocks and other structural and policy parameters from the estimated model as given, would a counterfactual history in which prices and wages had been more flexible in the post-WWII U.S. lead to more or less output growth volatility?

To summarize our analytical results, we find that there are several circumstances under which a higher degree of price (and/or wage) flexibility is destabilizing. Generally, the results depend upon two factors: (i) the source of shocks and (ii) the policy reaction function of the central bank. We find it useful to classify disturbances into two broad classes: “demand” and “supply” shocks. Examples of demand shocks include monetary policy shocks and preference shocks, i.e., shocks that mainly affect the natural rate of interest without having any effect on the natural level of output. Examples of supply shocks include technology shocks, variations in monopoly power in product and labor markets, and variations in distortionary taxes, i.e., shocks that mainly affect the natural level of output without having much effect on the natural rate of interest.²

First, consider demand shocks. For an increase in price flexibility to be destabilizing we find that the key condition is that the central bank does not raise/cut the nominal interest aggressively enough in response to movements in inflation. Intuitively, higher price flexibility

²The natural level of output is the output that would prevail if prices were flexible while the natural rate of interest is the real interest rate that would prevail if prices were flexible.

can trigger unstable inflation expectations if monetary policy does not act aggressively to counteract this by raising/cutting interest rates.³ If the interest rate response is weak, the result is precisely of the form analyzed by De Long and Summers (1986) and Tobin (1975) and anticipated by Keynes (1936) and Fisher (1923, 1925): Higher price flexibility *will* destabilize the real interest rate – the difference between the short term nominal interest rate (the policy rate) and expected inflation. Since aggregate demand depends upon the real interest rate, this destabilizes output as well.

In contrast to this earlier literature, however, we find that the condition under which this destabilization occurs is quite special. In particular, one needs to assume an interest rate reaction function for the central bank that does not correspond well to the one estimated on U.S. post-WWII data since it would require an interest rate response to inflation that is less than one-to-one. However, we find that this particular condition – that is, a small reaction of the policy rate in response to inflation – is satisfied if the demand shocks are large enough for the zero bound on the short-term nominal interest rate (ZLB) to be binding. This situation, of course, is faced by large parts of the world today. Interestingly, it was also the state of affairs at the time Keynes conjectured that increased price flexibility would be destabilizing. These results thus relate to a similar finding in the literature on the zero bound on the short-term nominal interest rate, see for example Eggertsson (2010), Christiano et al. (2011) and Werning (2011). In a distinct contribution to the literature, we show that our results can hold even at positive interest rates and away from the zero bound if the central bank cares excessively about output stabilization at the expense of inflation. While this may not apply to U.S. in the post-war data (with the possible exception of the 1970's), one can plausibly argue that examples of this may include developing countries where a heavily politicized central bank engages in output stabilization at the expense of inflation stabilization.

Second, consider supply shocks. Here we find that an increase in price flexibility is always destabilizing, in contrast to the result for demand shocks where it can go either way depending on policy. The reason is somewhat subtle. If monetary policy responds strongly to inflation then positive supply shocks increase output and more so the more flexible are prices. If monetary policy is unresponsive, however, then output decreases in response to positive supply shocks, and this decline is larger the more flexible are prices. Accordingly, the variance of output goes up with higher price flexibility regardless of the monetary policy reaction function. This latter effect of price flexibility, in the case where

³To be clear, we maintain the assumption on the parameters of the model so that equilibrium is always unique and determinate so that comparative statics are thus well defined.

monetary policy is unresponsive, is a generalization of the so called “paradox of toil” proposed in Eggertsson (2010) at the ZLB. Here we see that it can arise more generally as long as policy is unresponsive, with the implication that increased price flexibility is always destabilizing in face of supply shocks.

We find similar results in terms of economic welfare which we derive from the utility function of the representative household. For a typical monetary policy reaction function (for example, a Taylor rule) the result are even a bit stronger in that price higher flexibility can be counterproductive, since we find that there are many examples in which economic welfare goes down with more flexible prices, even when the output gap volatility goes down. The reason for this is that economic welfare does not only depend on output gap volatility but also the welfare weighted volatility of inflation. This term in social welfare typically goes up with higher price flexibility.

An explicitly derived social welfare function also allows us to analyze optimal monetary policy. Our results for optimal monetary policy are largely analogous to those in which policy follows a monetary policy reaction function that is consistent with postwar US data. In particular, higher flexibility will generally reduce output volatility (and improve welfare) for demand shocks (unless at the ZLB) and vice versa for supply shocks. An important consideration is that we need to make assumptions so that the first best cannot always be achieved with monetary policy alone, which is particularly relevant when considering supply shocks or demand shocks that are strong enough so that the ZLB is binding.

It is not of principal importance in our analytical model if only prices are made more flexible, or if wages and prices become more flexible at the same time (if wages are also rigid in the model), at least when we consider the Taylor rule for monetary policy. We show this explicitly in the model with both wage and price rigidities. Wage rigidities are an important addition to the model, however, when considering optimal policy. The reason for this is that in the model with price rigidities only, optimal policy can sometimes perfectly replicate the first best allocation (which is independent of price rigidities), while when both wages and prices are rigid, this is not possible. Thus, while assuming only price rigidities is quite innocuous when analyzing the main questions in the model with standard policy rules, it becomes more important to incorporate both nominal frictions in studying optimal policy. For some supply shocks, for example, technology shocks, we thus need to assume both price and wage rigidities to obtain the result that output volatility increases (and welfare decreases) with higher nominal flexibility. Those set of results are complementary to those in Galí (2012), who also reports similar numerical results in a model with both sticky prices

and wages.

We find that our key analytical results for individual shocks also apply in the estimated model. Moreover, crucially, for the estimated model, we find that output growth would have been less stable if prices/wages had counterfactually been more flexible than the historical estimates.⁴ Given our estimated policy rule – and since the zero bound was never binding in our sample (which runs from 1966 to 2004) – this reflects that “supply shocks” were a quite important driving force of the business cycle during this period. In particular, *inefficient supply shocks* driven by price/wage markup variations are non-negligible according to the estimation. Moreover, under the estimated parameter values, for supply shocks, the variance of output is quite sensitive to changes in the level of price/wage stickiness. Let us emphasize, however, that we also estimate other variants of the baseline Smets-Wouters medium scale DSGE model that provide alternate identification strategies and reinterpretation of the price/wage markup shocks (since those shocks have by some been argued to be “incredible” due to their size) and show that our quantitative results continue to hold or even strengthen (even if in those variations the size of markup shocks is greatly reduced – in some cases by a factor of a 100 — or even eliminated).

Quantitatively, the increased output growth volatility that results from higher nominal flexibility is far from trivial. In our baseline estimated model, the average annualized growth rate is 1.7 percentage points per year with a standard deviation of 2.2 percentage points. If we counterfactually assume that all prices are perfectly flexible, then the standard deviation of annualized output growth increases from 2.2 percentage points to 2.9 percentage points. If we assume that all prices and wages were perfectly flexible, then the standard deviation of annualized output growth increases from 2.2 percentage points to 4.4 percentage points, that is, it more than doubles. Thus, output growth – a traditional metric for the business cycle – would have been significantly more volatile.

The result from our estimated model is the same as in the numerical experiment reported in De Long and Summers (1986). The reason however, is different. Under their specification, price flexibility is destabilizing when demand shocks are perturbing the economy – but stabilizing when the driving force is supply shocks. Our estimated model implies the opposite. Nominal flexibility becomes destabilizing when supply shocks are mainly perturbing the economy, which account for a non-trivial fraction of total output volatility in our estimated model.

⁴We compute unconditional second moments of output growth in our estimated model since output is non-stationary in the model due to deterministic growth.

2 A Simple New Keynesian Model

We start by showing our key results in the standard three-equation New Keynesian model with price stickiness. Since this model has become standard by now, we do not write up the micro-foundations, which can be found in textbooks such as Woodford (2003). To fix notation we briefly summarize the main elements of model in the next paragraph.

Thus, consider the standard New Keynesian model with time-dependent pricing as in Calvo (1983). From the optimization problem of the firm, which chooses its price anticipating that it only gets to revisit this choice with an exogenous probability $1 - \alpha$ every period, we can derive the optimal pricing equation. We can do a log-linear approximation of the model and the firms' pricing decisions that implies the New Keynesian Phillips curve, or the "AS" equation

$$\pi_t = \kappa \hat{Y}_t - \kappa \hat{Y}_t^n + \beta E_t \pi_{t+1} \quad (1)$$

where π_t is inflation, \hat{Y}_t is output in log-deviation from steady state, and \hat{Y}_t^n is a disturbance term, often called the "natural level" of output, that has the following interpretation: It corresponds to the output that would be produced in case prices were flexible.

The parameter $\kappa \equiv \frac{(1-\alpha)(1-\alpha\beta)\phi+\sigma^{-1}}{\alpha} > 0$ measures the slope of the Phillips curve, where β is the discount rate, ϕ^{-1} is the Frisch elasticity of labor supply, σ is the intertemporal elasticity of substitution, and θ is the elasticity of substitution among different varieties of goods. We are primarily interested in what happens as we increase "price flexibility." We interpret this as increasing the exogenous probability of adjusting prices, that is $1 - \alpha$, which results in a higher κ .

More specifically, the composite term \hat{Y}_t^n is given by

$$\hat{Y}_t^n = \frac{1 + \phi}{\sigma^{-1} + \phi} \hat{A}_t - \frac{1}{\sigma^{-1} + \phi} \hat{\mu}_t + \frac{1}{\sigma^{-1} + \phi} \hat{\tau}_t^w \quad (2)$$

where A_t is productivity shocks, μ_t markup shocks of firms, and $\hat{\tau}_t^w$ is time-varying labor taxes. Observe that at this stage, these shocks appear in the AS equation in exactly the same way, hence we will for now simply refer to shock to the natural level of output as productivity shocks, A_t , or supply shocks. The distinction between these different sources of variation in the natural level of output will become relevant once we consider welfare, at which point we will revisit this notation.

Let us start with the exercise which has become relatively standard in the empirical and

theoretical literature on price rigidities. Consider an exogenous path for nominal spending

$$D_t \equiv P_t Y_t \quad (3)$$

given by

$$\Delta \hat{D}_t = \rho \Delta \hat{D}_{t-1} + \epsilon_t^d \quad (4)$$

where $\Delta \hat{D}_t$ is growth rate of D_t , $0 < \rho < 1$, and ϵ_t^d is an exogenous i.i.d. disturbance. The definition of nominal spending given by eqn.(3) implies that

$$\Delta \hat{D}_t = \pi_t + \hat{Y}_t - \hat{Y}_{t-1}. \quad (5)$$

What does eqn.(5) say? It says that an increase in nominal spending must, by definition, result in one of two things: Either an increase in the growth rate of prices (inflation), or an increase in the growth rate of output. Given that we take the path of demand as an exogenous process, it is then not altogether surprising that the higher the degree of price flexibility, that is the higher the κ , the “easier” it is to meet an increase in nominal spending by inflation without changing output much. Indeed, by using the method of undetermined coefficients and solving eqns.(1), (4), and (5), the solution for output can be expressed as

$$\hat{Y}_t = \frac{(1 - \rho\beta)}{(1 + \kappa - \rho\beta + \beta(1 - Y_y))} \Delta \hat{D}_t + Y_y \hat{Y}_{t-1}$$

where $Y_y \in (0, 1)$ is a function of the structural parameters of the model. Assuming $\rho = 0$ we get an analytical solution

$$VAR(\hat{Y}_t) = \Gamma * VAR(\Delta \hat{D}_t)$$

where $\Gamma = \left[\frac{1}{(1 + \kappa + \beta(1 - Y_y))} \right]^2$ and $VAR(X_t)$ represents variance of variable X_t .

It can now be shown that Γ is decreasing in κ , that is, the higher is the degree of price flexibility, the lower is the the variance in output (see Appendix A, this also holds for $0 < \rho < 1$). The intuition is straight-forward. As price flexibility increases, the instability in nominal demand is reflected in inflation rather than in output. Assuming a cash-in-advance constraint, it is common to interpret D_t as the nominal stock of money. On the basis of this, then, it would be tempting to conclude that the degree of “instability” in the real economy due to “monetary instability” is a simple function of the duration of price rigidities. Indeed,

this is often implicitly or explicitly what the literature does. As we show now, however, this conclusion is not warranted once we model monetary policy more explicitly and subject the economy to other shocks.

Instead of treating nominal demand as exogenous, let us now model it explicitly from the households maximization problem. In the standard New Keynesian framework this leads to an “IS” relationship given by

$$\hat{Y}_t = E_t \hat{Y}_{t+1} - \sigma(\hat{i}_t - E_t \pi_{t+1}) + \hat{\psi}_t - E_t \hat{\psi}_{t+1} \quad (6)$$

where \hat{i}_t is the nominal interest rate and ψ_t is an exogenous disturbance term that perturbs the preferences of the representative household. We will refer to this as “demand shock” since it only affects the IS equation.⁵

Meanwhile, we assume that monetary policy is given by a policy reaction function, that is the standard “Taylor rule” augmented by the zero bound

$$\hat{i}_t = \max(\beta - 1, \phi_\pi \pi_t + \phi_y \hat{Y}_t + \eta_t) \quad (7)$$

where $\phi_\pi, \phi_y > 0$ and η_t is a monetary policy shock. Since we define each variable in terms of deviation from steady state, the zero bound is now $\hat{i}_t \geq \beta - 1$. This closes the model.

To ensure a determinate equilibrium, see Woodford (2003), we assume that the following condition is satisfied⁶

$$\phi_\pi + \frac{1 - \beta}{\kappa} \phi_y > 1. \quad (8)$$

Finally, we assume that each of the exogenous processes A_t, ψ_t , and η_t follow a first order AR process with persistence ρ^i and i.i.d. component ϵ_t^i where i indexes A, ψ , or η .

What is important here, is that this system of equations implies that nominal demand, $\Delta \hat{D}_t$, is *endogenous*. It is determined by a host of factors, and in particular the monetary policy reaction function and the IS specification. Recall that before, the question was posed as: How does an exogenous shock to nominal demand influence output and prices? Since

⁵This specification cleanly separates the main effects we are interested in – that is, exogenous forces that perturb the IS equation on the one hand – “demand shocks” and exogenous forces that perturb the AS equation on the other – “supply shocks”. The preference shock and productivity shock are clear examples of shocks that affect only one of these margins, but there are other shocks that may affect both, such as exogenous variations in government spending (which both has a direct demand effect and a “wealth effect” via labor supply which changes the natural rate of output).

⁶Determinacy is required for the comparative static we study to be well defined. If there is indeterminacy it is not clear which equilibria to pick so whether increasing flexibility is stabilizing or not may depend on equilibrium selection in an arbitrary way.

nominal demand is by definition $\Delta\hat{D}_t = \pi_t + \hat{Y}_t - \hat{Y}_{t-1}$, it has to show up in either prices and output. In the model above, where nominal demand is endogenous, we see that there is no particular reason for any “shock”, be it monetary disturbance or any other kind, to show up in either inflation or output. In particular, it could just as well change the path for $\Delta\hat{D}_t$ which was exogenous before. Hence, we cannot conclusively state how the variance of output will change with an increase in κ . In fact, increasing price flexibility can now even increase volatility in nominal demand endogenously depending on how we specify monetary policy.

Consider first the demand shock $\hat{\psi}_t$. Proposition 1 shows how the variance of output depends on κ when the shock perturbing the economy is the demand shock ψ_t . Let the variance of output that can be attributed to a shock x_t be given by $VAR(\hat{Y}_t/x_t)$.

Proposition 1 *Suppose ψ_t follows an AR(1) process with persistence ρ_ψ . Then, the variance of output that can be attributed to ψ_t is given by*

$$VAR(\hat{Y}_t/\psi_t) = \left(\frac{(1 - \beta\rho_\psi)(1 - \rho_\psi)}{(1 - \rho_\psi + \sigma\phi_y)(1 - \beta\rho_\psi) + \sigma\kappa[\phi_\pi - \rho_\psi]} \right)^2 VAR(\psi_t)$$

Proof. *In Appendix A.* ■

The proof of this proposition is a straight-forward application of the method of undetermined coefficients. Taking the partial derivative of this expression with respect to κ then allows us immediately to state the following result in Proposition 2.

Proposition 2 *The effect of higher price flexibility on output variance is given by the following:*

$$\text{If } \phi_\pi - \rho_\psi > 0, \text{ then } \frac{\partial VAR(\hat{Y}_t/\psi_t)}{\partial \kappa} < 0$$

$$\text{If } \phi_\pi - \rho_\psi < 0, \text{ then } \frac{\partial VAR(\hat{Y}_t/\psi_t)}{\partial \kappa} > 0.$$

Proof. *In Appendix A.* ■

Thus, when the underlying shock is ψ_t , Proposition 2 shows that if monetary policy is responsive enough, as given by $\phi_\pi - \rho_\psi > 0$, output volatility decreases with price flexibility. If monetary policy is not responsive enough, as given by $\phi_\pi - \rho_\psi < 0$, then output volatility instead increases with price flexibility.

To provide intuition, it is useful to write out explicitly the solution and graph it up, assuming that ψ_t is the only source of economic fluctuations. Under this assumption, since

the model is linear and ψ_t is the only state variable, eqn.(8) guarantees a unique bounded solution which takes the form

$$\hat{Y}_t = Y_\psi \psi_t, \quad \pi_t = \psi_r \psi_t, \quad \text{and} \quad \psi_t = \rho_\psi \psi_{t-1} + \epsilon_t$$

where Y_ψ and π_ψ are coefficients to be determined. This implies that

$$\begin{aligned} E_t \hat{Y}_{t+j} &= \rho_\psi^j Y_\psi \psi_t \\ E_t \pi_{t+j} &= \rho_\psi^j \pi_\psi \psi_t. \end{aligned}$$

Consider now the solution in period t , which we subscript with S (for short run): $\hat{Y}_S = \hat{Y}_t = Y_\psi \psi_t$ once the economy has been perturbed by a shock $\psi_t = \psi_S \neq 0$. The IS equation can be combined with the policy rule to yield an aggregate demand, “AD” equation of the following form

$$(1 - \rho_\psi + \phi_y \sigma) \hat{Y}_S = -\sigma(\phi_\pi - \rho_\psi) \pi_S + (1 - \rho_\psi) \psi_S \quad (9)$$

where we have substituted $E_t \hat{Y}_{t+1} = \rho_\psi \hat{Y}_S$ and $E_t \pi_{t+1} = \rho_\psi \pi_S$. The AS equation is similarly

$$(1 - \rho_\psi \beta) \pi_S = \kappa \hat{Y}_S. \quad (10)$$

For later purposes, note here that the slope of the AD equation given by eqn.(9) depends on whether $(\phi_\pi - \rho_\psi) \geq 0$ while the slope of the AS equation given by eqn.(10) is always positive since $\kappa > 0$.

The two relationships are plotted in Figure 1 Panel (a) for the case in which $\phi_\pi > \rho_\psi$. The figure shows the effect of a negative demand shock, from AD_1 to AD_2 under two assumptions, that is, when prices are rigid or more flexible (shown via a steeper AS curve). We see that under rigid prices, a given drop in demand results in a steeper contraction (point A) compared to the case when prices are more flexible (point B). The reason for this is relatively simple: Consider first the AD equation which pins down the number of goods purchased by the consumers. In this economy, production is demand determined, that is, the firms produce as many goods as are demanded by the customers that show up in front of their doors. This demand, however, depends not on any measure of price rigidity, but instead (as we see in IS) only on expectations about future output and the difference between the real interest rate and the demand shock ($\psi_t - E_t \psi_{t+1}$).

To clarify things further, let us for a moment assume that $\rho_\psi = 0$. Then the expectation terms drop out since the economy is in steady state the next period. The central bank

responds to a negative demand shock in the short run by cutting the nominal interest rate (since $\phi_\pi > 0$). This cut, however, will be bigger the greater is the drop in inflation associated with the demand shock. As prices become more flexible, then, the central bank cuts the nominal interest rate by more, and thus has a bigger effect on demand. That is essentially the logic that underlies Figure 1 Panel (a).

Consider now the case when $\rho_\psi > 0$, in which case the shock becomes more persistent. The logic described above still applies: the central bank will try to offset the demand shock by interest rate cuts and thus stimulate demand. But now some additional effects come into play due to the persistence of the shock. A persistent shock influences aggregate demand in two ways, as can be seen in IS eqn.(6): a more persistent shock changes both expected inflation and expected output. In particular, we see from eqn.(9) that once we have substituted out for the policy rule, then a persistent negative shock can potentially reduce future inflation expectations to such an extent that it actually destabilizes demand. To see this, consider an increase in ρ_ψ for a given ϕ_π . As we see from eqn.(9), this means that the AD curve becomes steeper, suggesting that a given nominal interest rate cut (in response to a reduction in π_S) now leads to a smaller increase in demand because once the shock is persistent, it not only triggers a reduction in current nominal interest rate today, it also triggers expectations of lower inflation in the future. The lower expected inflation in the future, in turn, increases the real interest rate, thus offsetting some of the expansionary effect of the decline in the nominal interest rate today. If the shock is persistent enough, and the interest response (given by ϕ_π) weak enough, the effect given by lower expected inflation can be so strong that it dominates and the aggregate demand become upward sloping in output and inflation. We turn to this case next.

Figure 1 Panel (b) shows the effect of a demand shock in the short run when $\phi_\pi - \rho_\psi < 0$. We see that in this case an increase in price flexibility leads to a bigger output contraction, from point A to point B. The reason for this has already been hinted at above: the more flexible are prices, the more inflation expectations drop, thus leading to an increase in the real interest rate. Because $\phi_\pi - \rho_\psi < 0$, this drop in inflation expectations is not met by an aggressive enough reduction in the central bank nominal interest rate at time t . This is an example, then, of price flexibility being destabilizing in the face of demand shocks.

What is the interpretation of $\phi_\pi - \rho_\psi < 0$? Because ρ_ψ has to be between zero and one for the model to be stationary, this condition implies that $\phi_\pi < 1$. Recall our condition for

determinacy, eqn.(8), which implies that for a determinate equilibrium we require that

$$\phi_y > \frac{\kappa}{1 - \beta}(1 - \phi_\pi) > 0.$$

Intuitively, the condition implies that if the central bank puts little weight on inflation ϕ_π , and thus correspondingly larger weight on output ϕ_y (which is required for determinacy), then this leads to instability in aggregate demand in response to more price flexibility. In particular, greater price flexibility will trigger instability in inflation expectations, which in turn leads to more unstable demand.

Is this a realistic description of central bank behavior? As we will see once we estimate the model, this condition is not satisfied in the U.S. post-war data. It may, however, be satisfied in some countries where the central bank does not react sufficiently to inflation, but excessively to output volatility. But an even more important point, perhaps, (at least from a U.S. standpoint) is that the basic logic of the proposition does carry over to an empirical specification of U.S. policy if we take one additional property of the policy reaction function into account.

The key mechanism behind Proposition 2 is that the central bank does not respond sufficiently strongly to a deviation of inflation from target. In the proposition this occurs due to a low ϕ_π . As we can see in the policy rule given by eqn.(7) however, monetary policy can be unresponsive to inflation for two reasons: either because ϕ_π is small, or alternatively, if there are shocks so that the zero bound is binding and the central bank *cannot* respond to reduction in inflation. We analyze this case next, which also helps us connect to the recent literature on the zero bound.

We consider next the case when ψ_t becomes negative enough so that the zero bound on the nominal interest rate binds. To be more specific, let us consider the case in which $\psi_t - E_t\psi_{t+1} < 0$ and let us put a slightly different structure on the shock for tractability. In particular, consider a shock as in Eggertsson and Woodford (2003) in which $\psi_t = \psi_S < 0$ in period 0 and which reverts back to steady state $\psi_t = \bar{\psi}$ with a fixed probability $1 - \mu$ every period thereafter. Call the period in which it reverts back to steady state τ . Then it is easy to confirm (see for example, Eggertsson (2010)) that the solution for inflation and output is

$$\pi_S = \frac{\kappa(1 - \rho_\psi)}{(1 - \mu)(1 - \beta\mu) - \mu\sigma\kappa}\psi_S < 0 \tag{11}$$

$$\hat{Y}_S = \frac{(1 - \rho_\psi)(1 - \beta\mu)}{(1 - \mu)(1 - \beta\mu) - \mu\sigma\kappa} \psi_S < 0. \quad (12)$$

The next proposition follows.

Proposition 3 *Conditional on $\psi_t - E_t\psi_{t+1} < 0$, and the shock process outlined above so that the zero bound is binding, output drops the more, the more flexible are prices (higher κ).*

Proof. *In Appendix A. ■*

Hence, if the shock to ψ_t is large enough so that the zero bound is binding, an increase in price flexibility is no longer stabilizing, it instead is destabilizing regardless of the value of ϕ_π and ϕ_y . The logic of this proposition is in fact the same as we showed in Figure 1 Panel (b). The intuition for this relies heavily on the fact that the nominal interest rate does not respond strongly to the drop in inflation and output since it is stuck at zero. Consider now what an increase in price flexibility does. Not only does it lead to a drop in the price level today but because the shock is persistent, it also leads to expectation of future deflation. Because the real interest rate is the difference between the nominal interest rate and expected deflation, higher price flexibility thus leads to expectation of more deflation in the future, thus even increasing the real interest rate by more, creating a vicious deflationary spiral. As discussed in Eggertsson (2010), this spiral may not even converge.

We now move on to other shocks that we have introduced above. Proposition 4 summarizes how the variance of output depends on κ under different assumptions about shocks perturbing the economy. It does so for the exogenous shocks A_t and η_t and without considering the zero lower bound, as we believe the zero bound consideration is most interesting when triggered by demand shocks.

Proposition 4 *Suppose each of the following shocks are independent of one another (A_t, η_t), and follow an AR(1) with persistence ρ_i , $i = \eta, A$. Then the variance of output that can be attributed to each shock is given by*

$$\begin{aligned} VAR(\hat{Y}_t/A_t) &= \left(\frac{\kappa\sigma[\phi_\pi - \rho_A]}{[(1 - \rho_A + \sigma\phi_y)(1 - \beta\rho_A) + \kappa\sigma[\phi_\pi - \rho_A]]} \gamma_A \right)^2 VAR(A_t) \\ VAR(\hat{Y}_t/\eta_t) &= \left(\frac{\sigma(1 - \beta\rho_\eta)}{(1 - \rho_\eta + \sigma\phi_y)(1 - \beta\rho_\eta) + \sigma\kappa[\phi_\pi - \rho_\eta]} \right)^2 VAR(\eta_t). \end{aligned}$$

where $\gamma_A = \frac{1+\phi}{\sigma^{-1}+\phi}$.

Proof. *In Appendix A.* ■

The proof of this proposition is a straight-forward application of the method of undetermined coefficients. We can see from this proposition right away that the partial derivative of the variance of output with respect to κ depends fundamentally on what is the source of the variation in output and the responsiveness of monetary policy.

We summarize these signs in the next proposition.

Proposition 5 *The effect of higher price flexibility on output variance is given by the following:*

$$\frac{\partial \text{VAR}(\hat{Y}_t/A_t)}{\partial \kappa} > 0$$

and

$$\text{If } (\phi_\pi - \rho_\eta) > 0, \text{ then } \frac{\partial \text{VAR}(\hat{Y}_t/\eta_t)}{\partial \kappa} < 0$$

$$\text{If } (\phi_\pi - \rho_\eta) < 0, \text{ then } \frac{\partial \text{VAR}(\hat{Y}_t/\eta_t)}{\partial \kappa} > 0.$$

Proof. *In Appendix A.* ■

The proof of this proposition is obtained by taking a partial derivative of the expressions in Proposition 4 with respect to κ . Note that this proposition can be written for $\hat{\mu}_t$ and $\hat{\tau}_t^w$ instead of A_t by replacing γ_A with $\gamma \equiv \frac{1}{\sigma^{-1} + \phi}$ and ρ_A with ρ_μ or ρ_{τ^w} . In other words, the result for productivity shocks holds more generally for any shocks that change the natural rate of output (but do not directly affect the IS equation).

Let us now comment upon the intuition for the result. First, for the case of η_t , the intuition is exactly the same as for ψ_t . To see this, just note that if we substituted for the monetary policy reaction function given by eqn.(7) (assuming positive interest rates) into the IS equation given by eqn.(6), then the shock η_t appears exactly in the same way as $\psi_t - E_t\psi_{t+1}$. Thus a monetary disturbance – defined in this way – works in the same way as a “demand shock.”

Let us now turn to the supply shock. For the supply shock, we find that regardless of the monetary policy reaction function, the variance of output always increases with higher price flexibility. The reason for this is a bit subtle, and relies on the fact that while output increases in response to a positive technology shock when policy reacts strongly to inflation it decreases when the interest rate does not respond strongly enough (this is a generalization of the so-called paradox of toil, see Eggertsson (2010)). And both these reactions get exaggerated, as we will now see, the higher is the degree of price flexibility. This then increases output variance unambiguously.

Figure 1 Panel (c) shows the effect of a productivity shock when $\phi_\pi > \rho_A$ and policy responds strongly to inflation. A positive technology shocks shifts out the aggregate supply curve as it reduces the marginal costs of firms so that they can now produce more output for the same level of inputs. For this to show up in more aggregate output, however, the consumers will need to be induced to buy more. Under the assumption that $\phi_\pi > \rho_A$ we have already seen in the case of demand shocks that the AD curve is downward sloping because the central bank will cut the nominal interest rate in response to a drop in inflation. Consider first the case when the supply shock is i.i.d. so that $\rho_A = 0$. The increase in output then happens via cuts in the nominal interest rate, and the greater the drop in the price level, the bigger is the drop in the nominal interest rates. This then leads to a more robust expansion.

Consider now $\rho_A > 0$. The figure is unchanged for low enough value for ρ_A but there are now additional forces at work because the supply shock not only triggers a drop in the nominal interest rate, the fact that it is persistent may also affect expected inflation $E_t\pi_{t+1} = \rho_A\pi_A A_t$ (using the same argument as in the case of demand shocks). Note that this effect is contractionary, because it leads to lower future expected inflation which increases the real interest rate, thus contracting demand. Graphically, this means that the AD curve in Figure 1 Panel (c) is now steeper and the expansionary effect of the supply shock is smaller (but again more price flexibility leads to a bigger expansion as before).

If ρ_A is large enough, or alternatively ϕ_π low enough, so that $\rho_A < \phi_\pi$, then the contractionary effect of lower expected inflation is *dominating* and the AD curve becomes upward-sloping in the (Y_S, π_S) space as shown in Figure 1 Panel (d). As we can see here then technology shocks are contractionary. The reason has already been outlined. Now, improvement in technology shocks triggers deflationary expectations that increase the real interest rate. This force is not offset via cuts in the nominal interest rate to a sufficient extent so that demand contracts rather than expanding in response to technology improvements. The net result is a reduction in output. Once again the effect of price flexibility is important. In particular this effect is stronger the more prices are flexible because then the increase in expected deflation increases. Accordingly, as shown in Figure 1 Panel (d), the drop in output is bigger. Hence, more flexible prices lead to more extreme output movements and higher variance of output under both policy specifications.

3 Extensions

We now consider several extensions to our analysis above.

3.1 Welfare

Our focus so far has been on output volatility, partly because this has been a focus of the previous literature cited in the introduction. In the context of our model, however, another natural criterion is the welfare of the representative household. This criterion is closely related to output volatility because welfare can be written under certain conditions as the sum of output and inflation volatility.

As shown in Woodford (2003), the welfare of the representative household can be approximated via second order approximation to yield

$$W_t \propto - \sum_{t=0}^{\infty} \beta^t \left[\frac{\theta}{\kappa} \pi_t^2 + \left(\hat{Y}_t - \hat{Y}_t^e \right)^2 + t.i.p \right] \quad (13)$$

where *t.i.p.* denotes “terms independent of policy.” We have done this approximation around the efficient steady state, that is, the steady state that would be consistent with the first-best allocation. The term \hat{Y}_t^e corresponds to

$$\hat{Y}_t^e = \frac{1 + \phi}{\sigma^{-1} + \phi} \hat{A}_t \quad (14)$$

and denotes variations in the efficient rate of output. Observe the difference between the efficient rate of output \hat{Y}_t^e and the natural rate of output \hat{Y}_t^n given by eqn.(2) (again, the latter is the output that would be produced if prices were perfectly flexible). We see that while the natural rate of output is affected by variations in markups, labor taxes and productivity shocks, the efficient output is only affected by productivity shocks. Thus, while productivity shocks are examples of efficient variations in the natural level of output, variations in labor taxes and markup are examples of *inefficient output movement*. This suggests that there may be an important difference between the source of the supply shocks from a welfare point of view. The immediate implication of the derivation above is that from a welfare perspective the government does not want output to change in response to supply shocks such as $\hat{\tau}_t^w$, and $\hat{\mu}_t$ while it will in general want output to vary with changes in productivity A_t . Hence, while we did not need to make a distinction between different sources of supply shocks for our previous propositions, this distinction is relevant if we use the representative household

welfare as the criterion.

For an easier comparison with our earlier results, we can simplify (13) by considering the special case in which $\beta \rightarrow 1$.⁷ Then, if we take unconditional expectations and the limit above, we can express welfare as

$$W \propto - \left[\frac{\theta}{\kappa} VAR(\pi_t) + VAR(\hat{Y}_t - \hat{Y}_t^e) + t.i.p. \right]. \quad (15)$$

We can now use eqn.(15) to evaluate welfare implications of increased price flexibility.⁸

The welfare function has a relatively standard interpretation: welfare is reduced in the model if output deviates from the efficient level and if inflation deviates from zero. The weight on inflation depends inversely on the extent of price stickiness. We see that there are two important differences relative to the output variability criterion we studied before. First, output volatility is socially optimal to the extent that it reflects variations in the efficient level of output. Second, the government now not only cares about output (gap) volatility but also about inflation volatility. The reason why inflation matters for welfare is that it leads to price dispersion across the firms in the economy. That implies sectorial misallocation, firms are producing different amounts of output (since they are charging different prices) while it would be socially optimal for them all to be producing the same. This generates a welfare loss that is independent of the cost of output volatility. This distortion, however, becomes less and less important, the more flexible prices are, that is, as κ increases.

This suggests that the role of the inflation distortion as price flexibility increases is not obvious. The effect of inflation volatility on welfare as prices become more flexible is given by the derivative

$$\frac{\partial \frac{\theta}{\kappa} VAR(\pi_t)}{\partial \kappa} = -\theta \frac{1}{\kappa^2} VAR(\pi_t) + \theta \frac{1}{\kappa} \frac{\partial VAR(\pi_t)}{\partial \kappa}.$$

On the one hand, more flexible prices makes the *weight* on inflation volatility smaller, which lowers the weight on inflation variance in social welfare (this is the first term). On the other hand, an increase in price flexibility affects inflation volatility itself (this is the second term).⁹ Finally, note that the level of $VAR(\pi_t)$, which in turn depends on κ , also matters.

⁷Let us note here that we are not aware of anything in what follows that depends on this simplification. This is especially true since β is not a function of price flexibility κ so that none of our derivatives w.r.t. κ are affected and that the model is completely forward-looking. We make this assumption merely to simplify the exposition of the paper and link the welfare function to the last section.

⁸Note here that we are only considering the welfare effect of the element of the loss function that interacts with policy decisions, we do not consider how an increase in price flexibility may affect the term t.i.p, that is, the “terms independent of policy.”

⁹Note that in the appendix, it is clear that this derivative is positive: that is as prices become more

The net effect depends on what happens in general equilibrium, which in turn, depends on the assumed policy rule. The next proposition shows the sign of this derivative in our model given the assumed Taylor rule.

Proposition 6 *The effect of higher price flexibility on the welfare-weighted inflation volatility is given by*

$$\frac{\partial_{\kappa}^{\theta} VAR(\pi_t/j_t)}{\partial \kappa} > 0 \text{ if } \phi_{\pi} - \rho_j < \Gamma_j \text{ for } j = A, \psi \text{ and } \mu_t$$

$$\frac{\partial_{\kappa}^{\theta} VAR(\pi_t/j_t)}{\partial \kappa} < 0 \text{ if } \phi_{\pi} - \rho_j > \Gamma_j \text{ for } j = A, \psi \text{ and } \mu_t$$

where $\Gamma_j \equiv \frac{(1-\rho_j+\sigma\phi_y)(1-\beta\rho_j)}{\kappa\sigma}$.

Proof. *In Appendix A.* ■

This proposition shows that if the coefficient ϕ_{π} in the Taylor rule is sufficiently high, then an increase in price flexibility will reduce the welfare-weighted inflation volatility term, and this applies to either demand or supply shocks. Moreover, when the level of price stickiness is high, then for a given ϕ_{π} , it is more likely that the welfare-weighted inflation volatility term increases with higher price flexibility. We are now in a position to do welfare evaluation.

Let us start with demand shocks. This proposition is very similar to what we obtained in Proposition 2 for output volatility in the case of demand shocks. A key difference, however, is that in that proposition, $\phi_{\pi} - \rho_{\psi}$ only had to be greater than zero for price flexibility to reduce output volatility, a condition that is satisfied in most estimates of the policy reaction function in the United States. Here, however, the critical value is determined by a coefficient Γ_{ψ} . This coefficient can easily be different from zero. In particular, if we substitute values common in the literature (see for example, Table 1) we find that this number is quite large, for example, 1.23 based on the parameters from Table 1. This implies a bound of 2.13 for ϕ_{π} , which is higher than for example, the estimated value of 1.5 found by Taylor (1993) that we use throughout this section as a benchmark. Thus, according to this benchmark – at least in this simple model – welfare (from the part corresponding to inflation) is reduced as prices become more flexible due to the fact that inflation volatility increases enough to compensate the lower weight it gets in the welfare function.

Which effect is stronger for demand shocks? The reduction in welfare due to the increase in inflation volatility or the increase in welfare due to lower output volatility? The next proposition answers that question.

flexible, variance of inflation increases.

Proposition 7 *The total effect of higher price flexibility on welfare losses generated by demand shocks as measured by eqn.(15) is given by*

$$\begin{aligned} \frac{\partial W(\cdot, \psi_t)}{\partial \kappa} &< 0 \text{ if } (\phi_\pi - \rho_\psi) < \Lambda_\psi \\ \frac{\partial W(\cdot, \psi_t)}{\partial \kappa} &> 0 \text{ if } (\phi_\pi - \rho_\psi) > \Lambda_\psi \end{aligned}$$

where $\Lambda_\psi \equiv \frac{\theta(1-\beta\rho_\psi)(1-\rho_\psi+\sigma\phi_Y)}{\sigma(2(1-\beta\rho_\psi)^2+\kappa\theta)}$.

Proof. *In Appendix A.* ■

This proposition shows that for ϕ_π low enough, welfare is decreasing as price flexibility increases. Observe that this may be the case even when $(\phi_\pi - \rho_\psi) > 0$, where output volatility goes down as prices become more flexible. This is because the weight on relative price distortions is strong enough to compensate for the positive effect on welfare that is triggered by the decline in output volatility. Also note that for a given ϕ_π , welfare is more likely to decline with increased price flexibility when we start at a level of high price rigidity. Perhaps somewhat surprisingly, the critical value of ϕ_π needed to have welfare improvement is higher than many empirical estimates of this coefficient. Using the numerical example in Table 1, we see that the condition in the proposition applies as long as $\phi_\pi < 2.00$. Thus, conditional on demand shocks driving the business cycle, even if higher price flexibility reduces output volatility, it reduces aggregate welfare due to the relative price distortions it creates, as long as $\phi_\pi < \rho_\psi + \Lambda_\psi$, a condition that is satisfied in our benchmark of 1.5.

Let us now turn to supply shocks. To start with, consider inefficient supply shocks (for example, μ_t), in which case $\hat{Y}_t^e = 0$. As we have already documented in Proposition 5, output volatility increases with more flexible prices for these shocks. Proposition 6 illustrates that the weighted inflation volatility term is also decreasing in price flexibility as long as $\phi_\pi - \rho_\mu < \Gamma_\mu$, which as we have already seen is generally satisfied. It follows that a sufficient condition for welfare to be decreasing in price flexibility is that $0 < \phi_\pi - \rho_\mu < \Gamma_\mu$. Note that this condition is in general not necessary. The necessary condition is a bit more complex. Since the sufficient condition is typically satisfied for the most empirically relevant parameters, we only report the necessary condition in the appendix.

Proposition 8 *A sufficient condition for higher price flexibility to have a negative effect on welfare losses due to inefficient supply shocks, μ_t and τ_t^w , is given by*

$$0 < \phi_\pi - \rho_\mu < \Gamma_\mu$$

Proof. *In Appendix A.* ■

Finally, consider the effect on welfare of efficient supply shocks, such as productivity shocks. A key difference relative to the inefficient supply shocks is that now some of the variations in output due to the shocks are in fact desirable since they trigger variation in the efficient level of output Y_t^e and so while we can still use Proposition 6 to find the effect of the supply shocks on inflation variability, now Proposition 5 is no longer sufficient.

As a step towards the overall effects on welfare, we first show the effect on the variance of the welfare-relevant output gap, $VAR(\hat{Y}_t - \hat{Y}_t^e)$, when the shock is A_t .

Proposition 9 *The effect of higher price flexibility on the welfare relevant output gap for efficient supply shocks, A_t , is given by*

$$\begin{aligned} \text{If } (\phi_\pi - \rho_A) > 0, \text{ then } \frac{\partial VAR(\hat{Y}_t - \hat{Y}_t^e/A_t)}{\partial \kappa} < 0 \\ \text{If } (\phi_\pi - \rho_A) < 0, \text{ then } \frac{\partial VAR(\hat{Y}_t - \hat{Y}_t^e/A_t)}{\partial \kappa} > 0. \end{aligned}$$

Proof. *In Appendix A.* ■

We thus see that the variance of the welfare-relevant output gap increases with higher price flexibility if monetary policy is not responsive enough (as given by $(\phi_\pi - \rho_A) < 0$), while it decreases with higher price flexibility if monetary policy is responsive enough (as given by $(\phi_\pi - \rho_A) > 0$).

Now we have both the pieces required to evaluate the effects on welfare of increased price flexibility, with Proposition 6 showing the effects on the welfare-weighted inflation term and Proposition 9 on the welfare-relevant output gap term. Note that it is immediately clear that for $(\phi_\pi - \rho_A) < 0$, welfare is decreasing unambiguously as both the terms increase with κ . We can however establish a more precise condition analytically that shows which of the effects dominate when $0 < (\phi_\pi - \rho_A) < \Gamma_A$ as then, while the output gap variability increases, the welfare-weighted inflation variability increases. The next proposition presents our main welfare result regarding technology shocks.

Proposition 10 *The total effect of higher price flexibility on welfare losses generated by efficient supply shocks, A_t , as measured by eqn.(15) is given by*

$$\begin{aligned} \frac{\partial W(\cdot \setminus A_t)}{\partial \kappa} < 0 \text{ if } (\phi_\pi - \rho_A) < \Lambda_A \\ \frac{\partial W(\cdot \setminus A_t)}{\partial \kappa} > 0 \text{ if } (\phi_\pi - \rho_A) > \Lambda_A \end{aligned}$$

where $\Lambda_A \equiv \frac{\theta(1-\beta\rho_A)(1-\rho_A+\sigma\phi_Y)}{\sigma(2(1-\beta\rho_A)^2+\kappa\theta)} < \Gamma_A$.

Proof. *In Appendix A.* ■

We see that the condition for efficient supply shocks to have a negative welfare effect is essentially the same as for demand shocks. In particular, the value of $\phi_\pi - \rho_A$ has to be less than Λ_A , which in the context of our numerical example suggests that ϕ_π has to be less than 2.00. This may seem somewhat puzzling as we know that at full flexibility, productivity shocks are completely efficient and we get to the first-best allocation in this simple model (thus, welfare with full price flexibility must be higher than with full rigidity). The resolution of the puzzle is that similar to demand shocks, for a given ϕ_π , as prices move from perfectly rigid to more flexible, while welfare losses increase at first, after a critical point they will ultimately decline, as made further clear in the next section with numerical examples (see Figure 2).

Observe also that this condition for efficient shocks is a bit tighter than the sufficient condition in Proposition 8 for inefficient shocks, where ϕ_π only needed to be less than 2.13. This is not surprising, as the variability of the output gap $Y_t - Y_t^e$ is decreasing for efficient supply shocks as prices become more flexible when $(\phi_\pi - \rho_A) > 0$ (while it is increasing for inefficient shocks for all ϕ_π) so that the negative welfare effect of higher price flexibility comes once again about due to the fact that welfare weighted inflation volatility is increasing and sufficiently high, thus triggering welfare-reducing price dispersion that outweighs the decrease in output gap variability. Finally, comparing the condition for welfare-weighted inflation volatility with overall welfare, as expected, $\Lambda_A < \Gamma_A$, as the decreased output gap variability effects makes the bound on $(\phi_\pi - \rho_A)$ required to have lower welfare with increased price flexibility smaller.

3.2 Alternative Policy Rules

So far, we have considered a simple Taylor-type rule, as given by eqn.(7), as a description of monetary policy. We now consider several variants of such rules that are popular in applied work, allowing for a welfare-relevant output gap, interest rate smoothing, and a response to the growth rate of the output gap (this is motivated by our quantitative model's interest-rate rule specification). Overall, we do not find that these extensions have a significant effect on

the results qualitatively. The rules we consider are

$$\begin{aligned}\hat{i}_t &= \phi_\pi \pi_t + \phi_y \left(\hat{Y}_t - \hat{Y}_t^e \right) \\ \hat{i}_t &= \rho_i \hat{i}_{t-1} + (1 - \rho_i) \left[\phi_\pi \pi_t + \phi_y \left(\hat{Y}_t - \hat{Y}_t^e \right) \right] \\ \hat{i}_t &= \rho_i \hat{i}_{t-1} + (1 - \rho_i) \left[\phi_\pi \pi_t + \phi_y \left(\hat{Y}_t - \hat{Y}_t^e \right) \right] + \phi_{d,y} \Delta \left(\hat{Y}_t - \hat{Y}_t^e \right).\end{aligned}$$

We show in Figure 2 results for both the variance of output and welfare for both demand and supply (markup and technology) shocks as a function of $1/(1-\alpha)$, which is the expected duration of the price contract. For this exercise, we use the same parameters as in Table 1 as well as $\phi_\pi = 1.5$, $\phi_y = 0.125$, $\rho_i = 0.9$, $\phi_{d,y} = 0.125$, $\theta = 10$, and $\phi = 2$.¹⁰

Note that this parametrization implies that monetary policy is “responsive.” In line with our analytical results, Figure 2 shows that for all of the Taylor rule specifications, for demand shocks, the variance of output decreases with increased price flexibility while for supply shocks, it increases. Thus, the same result applies across all the policy rules. In the case of the unresponsive we find the opposite result for demand shocks (as in the analytical section) while the sign remains the same for supply shocks.¹¹

Moving to welfare, we can also confirm our theoretical results across all policy rules. The figure shows clearly that for all the Taylor rule specifications and for all the shocks, welfare decreases with increased price flexibility for a high enough level of price stickiness. Once prices are flexible enough, however, then welfare improves with further increases in price flexibility, much as our theoretical results suggested. Interestingly, this reflection point occurs later for the alternative policy rules, suggesting that our result that increasing price flexibility can be welfare-reducing applies to an even broader parameter range for these alternative policy rules.¹²

3.3 Optimal Monetary Policy

So far, we have discussed the effects on output volatility and welfare of increased price flexibility while modeling monetary policy as following an interest-rate rule. Thus, the

¹⁰Our baseline parameterization in Table 1 of $\kappa = 0.02$ corresponds to duration of 3.2 quarters. We only provide numerical results here since analytical results are tedious with interest rate smoothing.

¹¹Since it is not empirically the most relevant (except at the ZLB), we do not report the unresponsive case here to save on space.

¹²Notice that for preference and markup shocks, the results in the Figure are identical whether we have output or the welfare-relevant output gap in the Taylor rule since these shocks do not perturb the efficient level of output.

increase in price flexibility does not change the policy reaction function of the government at the same time. How sensitive is our conclusion to allowing for the feature that an increase in κ may simultaneously change government behavior, for example, ϕ_π or ϕ_y ? In order to address this question we need to have some theory of how the government behaves in response to changes in the level of stickiness in price setting.

One approach is to assume that policy is determined to maximize social welfare, so that policy may then endogenously react if there is a change in κ . Hence the government maximizes eqn.(15) subject to eqns.(1), (6), and the zero bound on the short term nominal interest rate.¹³ Consider first optimal policy under discretion (Markov Perfect equilibrium), that is, the government maximizes welfare but is unable to commit to future policy. Then the first-order conditions of the government maximization problem can be combined to yield the following relationship between output and inflation

$$\theta\pi_t + (\hat{Y}_t - \hat{Y}_t^e) = 0. \quad (16)$$

We see that this relationship, the so-called “targeting rule,” is independent of the degree of price flexibility. In particular, observe that if the only shocks in the economy are A_t and ψ_t (and the zero bound is not binding) this relationship implies an equilibrium in which $\pi_t = \hat{Y}_t - \hat{Y}_t^e = 0$ at all times. This means that neither output nor inflation volatility depend upon the degree of price rigidity. Compared to our previous policy rule in eqn.(7), discretion thus corresponds to the special case when $\phi_\pi \rightarrow \infty$, that is, the central bank completely offsets any effect of preference and technology shocks on inflation. It is easy to see that in this case, also, changes in price rigidities have no effect on welfare since the central bank is fully replicating the flexible price, and thereby, efficient allocation. Or, to summarize:

Proposition 11 *Output and inflation volatility, as well as welfare, is independent of price flexibility if policy obtains the first-best allocation.*

Proof. *In Appendix A.* ■

This result, however, is relatively special and relies heavily on the “divine coincidence” feature demonstrated by Blanchard and Galí (2007) in the most simple variation of the New Keynesian model. It says there is no trade-off between inflation and output gap in response to technology and preference shocks. Accordingly, the first best can be achieved. This divine coincidence is absent in a more general setting (with wage frictions), as we shall shortly see.

¹³All the details of the derivation are contained in the appendix.

Moreover, for a more general specification of the shocks, and when the first best is no longer obtained, our previous results are unchanged as we now demonstrate.

Let us first consider an example where the first-best is not achieved due to the zero bound. Recall that under the Taylor rule, demand shocks were destabilizing if the policy did not respond aggressively enough to inflation (this is Proposition 2). This result is absent in the discussion above, since optimal discretion is equivalent to $\phi_\pi \rightarrow \infty$. The zero bound on the nominal interest rate, however, brings this key result back, even if the government is maximizing welfare under discretion. In particular, Eggertsson (2008) shows that one obtains exactly the same equilibrium under optimal monetary policy under discretion as we have already analyzed in eqns.(11) and (12). It follows that Proposition 3 also applies if the government conducts policy under discretion. Hence, at the zero bound, the more flexible the prices, the greater the drop in output. Moreover, we show in Appendix A that welfare also declines with increased price flexibility in this case.

Let us now consider a case when the first best is not achieved for a more general specification of supply shocks. Consider an inefficient supply shock μ_t (or alternatively τ_t^w). In this case, $\hat{Y}_t^e = 0$, and there is a trade-off between inflation and output. In this case we can prove the following proposition:

Proposition 12 *Suppose policy is set optimally under discretion and μ_t follows an AR(1) process. Then the variance of output is given by*

$$VAR(Y_t) = \theta^2 \left(\frac{\kappa}{1 + \kappa\theta - \beta\rho_u} \right)^2 VAR(\mu_t)$$

which is always increasing in price flexibility so that

$$\frac{\partial var(Y_t)}{\partial \kappa} = \frac{\theta^2(1 - \beta\rho_u)2\kappa}{(1 + \kappa\theta - \beta\rho_u)^3} VAR(\mu_t) > 0.$$

Similarly, welfare is decreasing in price flexibility

$$\frac{\partial W}{\partial \kappa} < 0$$

if $\frac{1+\kappa\theta}{1+2\kappa\theta} > \beta\rho_u$.

Proof. *In Appendix A.* ■

This is a close analogue to Propositions 5 which showed that output variability always increases under a Taylor rule (and the complementary Proposition 8 for welfare). Thus,

with an inefficient shock μ_t and under optimal monetary policy, not only does the variance of output increase, but welfare can also be reduced with increased price flexibility as long as $\frac{1+\kappa\theta}{1+2\kappa\theta} > \beta\rho_\mu$. In particular, with i.i.d. shocks ($\rho_\mu = 0$), welfare always declines when inefficient supply shocks hit the economy and monetary policy is conducted optimally under discretion. Moreover, as before with a Taylor rule, the condition for welfare to decline with additional increased price flexibility becomes harder to fulfill as prices become more flexible.¹⁴ Let us also point out that the policy under the optimal commitment has a similar flavor as outlined above.¹⁵

The divine coincidence that allows monetary policy to achieve the first best in response to technology and preference shocks is not a general feature of New Keynesian models. As soon as we introduce more realistic nominal frictions, a trade-off between inflation and output appears. We make this clear in the next section when we extend the model to incorporate rigid wages. In particular, one can show that output volatility is increasing in price flexibility for shocks that imply a trade-off between inflation and output gap (such as technology shocks) and that welfare is also decreasing in some of our numerical experiments.

3.4 Price and Wage Stickiness

So far, we have been using the basic New Keynesian model featuring only price stickiness. However, estimated models in the literature (including the one in the next section) typically feature both price and wage stickiness. It is worthwhile to consider how our results are affected if we allow for both price and wage stickiness. We undertake this exercise next.

Generally speaking, our main results continue to apply in the extended model: increased price flexibility (now measured as an increase in both prices and wage flexibility) can destabilize both output and welfare, depending on the policy. The conditions under which this applies are largely parallel to our previous discussion although in some cases we can only show this via numerical examples. Perhaps the main new element is that in the model with wage rigidities, the divine coincidence no longer applies. As we will see, this implies that technology shocks now create a trade-off between inflation and output gap unlike in the basic New Keynesian model. This will imply that under optimal policy (under discretion, for simplicity), an increase in price flexibility typically destabilizes both output and welfare even for technology shocks. Thus, we show that the distinction between efficient and ineffi-

¹⁴In the appendix, we also show that the persistence of the shock matters for our condition in the proposition as it affects strongly the variance of the welfare-weighted inflation term.

¹⁵One simply needs to modify eqn.(16) to include $(\hat{Y}_t - \hat{Y}_t^e) - (\hat{Y}_{t-1} - \hat{Y}_{t-1}^e)$ instead of $(\hat{Y}_t - \hat{Y}_t^e)$.

cient supply shocks is not as stark from a normative perspective once we allow for additional frictions in the baseline sticky price model.

We use a standard model of price and wage stickiness as described in Woodford (2003). The private sector equilibrium conditions are given by

$$\hat{Y}_t = E_t \hat{Y}_{t+1} - \sigma(i_t - E_t \pi_{t+1}^p - \hat{\psi}_t + E_t \hat{\psi}_{t+1}) \quad (17)$$

$$\pi_t^p = \kappa_p(Y_t - Y_t^n) + \xi_p(\hat{w}_t - \hat{w}_t^n) + \beta E_t \pi_{t+1}^p \quad (18)$$

$$\pi_t^w = \kappa_w(Y_t - Y_t^n) - \xi_w(w_t - \hat{w}_t^n) + \beta E_t \pi_{t+1}^w \quad (19)$$

$$\hat{w}_t = \hat{w}_{t-1} + \pi_t^w - \pi_t^p \quad (20)$$

where π_t^p now stands for price inflation, π_t^w for wage inflation, and \hat{w}_t for the real wage. Moreover, the expressions for the natural level of output \hat{Y}_t^n and the natural level of real wages \hat{w}_t^n are now given by

$$\hat{Y}_t^n = \hat{Y}_t^e = \frac{1 + \nu}{\sigma^{-1} + \nu} A_t; \quad \hat{w}_t^n = \frac{(1 + \omega_p)\sigma^{-1} + \nu - \omega_p}{\sigma^{-1} + \nu} A_t.$$

In terms of parameters, we have $\nu \equiv \frac{v_{hh}}{hv_h}$, $\phi_h \equiv \frac{f(h)}{hf'(h)}$, $\omega_w = \nu\phi_h$, $\omega_p = \nu - \omega_w$, $\xi_w = \frac{(1-\alpha_w)(1-\alpha_w\beta)}{\alpha_w(1+\nu\theta_w)}$, $\xi_p = \frac{(1-\alpha_p)(1-\alpha_p\beta)}{\alpha_p(1+\omega_p\theta_p)}$, $\kappa_w = \xi_w(\omega_w + \sigma^{-1})$, and $\kappa_p = \xi_p\omega_p$, where $f(h)$ is the production function and ν is the Frisch elasticity of labor supply.¹⁶ For details on this notation, please see Appendix B.

Note that compared to the model with simply sticky prices, in the price Phillips curve (18) there is now an additional term, the real wage gap, that is the gap between real wages and its natural counterpart. Moreover, because of sticky wages, there is now also a wage Phillips curve given by eqn.(19). Finally, eqn.(20) closes the model by specifying a law of motion for real wages. When we consider a Taylor rule specification, we use the same formulation as in the previous section.

In terms of welfare, as shown in Woodford (2003), the utility of the representative household can be approximated via second order approximation around the efficient steady-state to yield, after taking the $\beta \rightarrow 1$ approximation and unconditional expectations

$$W \propto - \left[\lambda_p VAR(\pi_t^p) + \lambda_w VAR(\pi_t^w) + \lambda_x VAR(\hat{Y}_t - \hat{Y}_t^e) + t.i.p. \right] \quad (21)$$

¹⁶We will use $f(h) = h^\gamma$ in our numerical experiments.

where $\lambda_p = \frac{\theta_p \xi_p^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi_h^{-1} \xi_w^{-1}}$, $\lambda_w = \frac{\theta_w \phi_h^{-1} \xi_w^{-1}}{\theta_p \xi_p^{-1} + \theta_w \phi_h^{-1} \xi_w^{-1}} > 0$, and $\lambda_x = \frac{\sigma^{-1} + \omega}{\theta_p \xi_p^{-1} + \theta_w \phi_h^{-1} \xi_w^{-1}} > 0$. We will use eqn.(21) to evaluate the welfare implications of increased price and/or wage flexibility for demand and technology shocks.

We are able to show some analytical results, as well as provide a sharp characterization overall, by making an additional assumption that the slope of the two Phillips curves is equal, that is, $\kappa_p = \kappa_w = \kappa$. Earlier we have interpreted the increase in flexibility as the thought experiment that prices become more flexible. A natural analog here is that both prices and wage flexibility increase, which once again can be characterized via an increase in $\kappa = \kappa_p = \kappa_w$. That is the approach we take in the remainder of the section. This assumption is one element that distinguishes our results from those in Galí (2011).

Using this parameter restriction, eqns.(17)-(20) can be simplified to yield

$$\pi_t^p = \kappa(\hat{Y}_t - \hat{Y}_t^n) + \beta E_t \pi_{t+1}^p + \kappa \frac{1}{\omega_p} (\hat{w}_t - \hat{w}_t^n) \quad (22)$$

$$\hat{Y}_t = E_t \hat{Y}_{t+1} - \sigma(i_t - E_t \pi_{t+1}^p - r_t^e) \quad (23)$$

$$\Delta \hat{w}_t = -(\xi_w + \xi_p)(\hat{w}_t - \hat{w}_t^n) + \beta E_t \Delta \hat{w}_{t+1} \quad (24)$$

where a key observation is that eqn.(24) yields a unique bounded solution for \hat{w}_t only as a function of the exogenous shock \hat{w}_t^n .¹⁷ This means that eqns.(22) and (23) reduce to exactly the same equations as before except for the important difference that now supply shocks will in general also have an effect on eqn.(22) through $\hat{w}_t - \hat{w}_t^n$, that is independent of movement in the efficient rate of output. Efficient supply shocks will thus trigger a trade-off between the output gap and inflation and thus violate the divine coincidence, in a manner similar to markup shocks in the baseline model with only price stickiness. We are now in a position to see how our previous results generalize to this environment. Let us start with the case in which the government follows a Taylor rule and then move on to optimal policy.

For demand shocks, the results are particularly clear under the Taylor rule when wages are sticky. It follows directly from eqns.(22)-(24) that we can generalize our proposition for the aggregate demand shock ψ_t to the model with both price and wage stickiness since in this case $\hat{w}_t = \hat{w}_t^n = 0$ and the two models are actually identical (hence Propositions 1, 2, 3, 6 and 7 all generalize to this environment). Things are a little bit trickier when we study

¹⁷To see this subtract eqn.(18) from eqn.(19) and use $\Delta \hat{w}_t = \pi_t^w - \pi_t^p$ to obtain

$$\Delta w_t = -(\xi_w + \xi_p)(w_t - w_t^n) + (\kappa_w - \kappa_p)(Y_t - Y_t^n) + \beta E_t \Delta w_{t+1}.$$

When $\kappa_w = \kappa_p$, we obtain eqn.(24). The exact solution for \hat{w}_t is provided in Appendix B.

technology shocks, however, since now there will be an effect via the wage gap $\hat{w}_t - \hat{w}_t^n$ in eqn.(22).

The results for supply shocks when we assume the Taylor rule, while not identical as in the case of demand shock, generally apply in the numerical experiments we have done. In particular, we find that an increase in price flexibility in general increases output volatility and reduces aggregate welfare when the response of interest rates to inflation is not very high and vice-versa. We report our calibration of the model with price and wage rigidities in Table 1 and report a simple example below in Figure 3 where we consider both the responsive and non-responsive cases. Note that for both cases, the variance of output increases and welfare decreases as we increase nominal flexibility.¹⁸ These constitute numerical counterparts to our Proposition 5 and 10.

Let us now move to optimal policy. We have already seen that if only demand shocks are perturbing the economy, then the sticky wage and price economy is isomorphic to the sticky price one. Accordingly, optimal policy in response to demand shocks is the same across the two models. What is of more interest is how the two models differ in response to efficient supply shocks. There we see a substantive difference. The reason for this is that the model with wage and price frictions has the realistic feature that the government cannot achieve the first best in response to supply shocks. Instead, they create a trade-off between inflation and output gap so that it is no longer the case that policy will fully offset these shocks. Appendix B shows that now the targeting rule eqn.(16) is replaced by

$$\pi_t^p + \chi_w \Delta \hat{w}_t + \chi_x (\hat{Y}_t - \hat{Y}_t^e) = 0 \quad (25)$$

where $\chi_w = \frac{\theta_w \phi_h^{-1} (\omega_w + \sigma^{-1})}{\theta_p \omega_p + \theta_w \phi_h^{-1} (\omega_w + \sigma^{-1})}$ and $\chi_x = \frac{\sigma^{-1} + \omega}{(\theta_p \omega_p + \theta_w \phi_h^{-1} (\omega_w + \sigma^{-1}))}$. Thus now, a new term, wage growth, appears in the targeting rule.

As before, in the targeting rule eqn.(25), the degree of price/wage stickiness does not appear directly. The key point though is that it is no longer the case that if productivity shocks are perturbing the economy, then there is an equilibrium in which $\pi_t = \hat{Y}_t - \hat{Y}_t^e = 0$ at all times as in the baseline model. Instead, the policymaker will trade off inflation and the output gap in response to a technology shock and this trade-off will in general depend upon price rigidities. This in turn will lead to a greater degree of output volatility and a reduction in welfare for a reasonable parameterization of the model, as we illustrate in Figure 4.

To summarize, we have shown that in a model with both wage and price rigidities and

¹⁸Thus, even for the responsive case, the response of interest rates to inflation is not high enough for welfare to increase with increased price flexibility.

under a Taylor rule, for demand shocks, the same analytical results apply as with price rigidities only while for supply shocks, the same results hold in our numerical example. Moreover, now the first best is no longer achieved so that under optimal policy, efficient technology shocks trigger a trade-off between inflation and output gap stabilization. We show numerically that under optimal policy with technology shocks, output volatility is increasing in price/wage flexibility and welfare can be decreasing.¹⁹

So far, we have shown in several model variants the effects on output volatility of increased price/wage flexibility. Our propositions show that the source of shocks and the endogenous response of monetary policy are the most important determinants. In other words, the answer to the question in the title of the paper “depends,” for example, on the relative size of the demand and supply shocks and on the monetary policy reaction function. Accordingly, it remains to determine what channel is most empirically relevant. This is what we now turn to using an estimated medium-scale DSGE model.

4 Quantitative Experiment

In this section, we conduct a quantitative evaluation of the effects of greater price/wage flexibility on output volatility. As we have emphasized, this effect depends crucially on the underlying shocks driving the economy and the endogenous response of monetary policy. To explore which results are of most empirical relevance for the U.S., we fit the well-known Smets and Wouters (2007) model to U.S. data, and estimate the structural parameters and the underlying shocks. Conditional on the estimated values for all other parameters of the model, we then ask the following counterfactual question: Does increasing the frequency of price/wage adjustment lead to higher output growth volatility in the model? We particularly focus on the counterfactual case where prices/wages are completely flexible and find that the answer is yes.

Which shocks drive this result? We find that the main driving forces are supply shocks such as technology shocks and shocks that trigger variations in price and wage markups. Shocks to markups have been criticized in the literature (see for example, Chari et al. (2009)) for being implausible and poorly identified. To address this criticism, we estimate two additional models: we consider the model of Galí et al. (2011) and a model in the spirit of de Walque et al. (2006). In the model of Galí et al. (2011), the role of wage markup shocks is drastically reduced as the model enables a separate identification of labor supply shocks

¹⁹Clearly, the same applies for markup variations as with price rigidities only.

and the estimation features measurement errors on wages. The model of de Walque et al. (2006) completely shuts down price markup shocks by introducing sector-specific productivity shocks in a flexible price sector. In these extensions, we find once again that an increase in price/wage flexibility would increase overall output volatility. In fact, this holds true under certain conditions even if we completely shut down variations in wage and price markups.

4.1 A Medium-Scale DSGE Model: The Smets-Wouters model

We refer the reader to the Smets and Wouters (2007) paper for a detailed description of the model. Here we only lay out the basic model features and introduce relevant notation while presenting the log-linear equations in Appendix C. Households in the model face an infinite-horizon problem and maximize expected discounted utility over consumption and leisure, with the discount factor given by β . The utility function is non-separable over consumption and labor effort. There is a time-varying external habit formation in consumption. The intertemporal elasticity of substitution is given by σ_c , the elasticity of labor supply by σ_l , and the habit parameter by h .

Households supply labor to a labor union, which differentiates the homogenous labor input. The elasticity of substitution over the differentiated labor services is time-varying and modeled as in Kimball (1995), where ε_w represents the curvature of the aggregator function. The union enjoys some monopoly power over setting wages, which are sticky in nominal terms. Wage stickiness is modeled following Calvo (1983). The constant probability of not adjusting wages is given by ξ_w , with wages that do not adjust partially indexed to past inflation, with the extent of indexation given by ι_w . The steady-state mark-up in the labor market is given by λ_w . Households also rent capital services to firms and in deciding how much capital to accumulate, take into account capital adjustment costs which enter as a function of change in investment. The steady-state elasticity of the capital adjustment cost function is given by φ . Moreover, the model features variable capital utilization rate, with the dependence of the degree of capital utilization on the rental rate of capital a function of the parameter ψ . Capital depreciates at the rate δ .

Firms produce differentiated goods using labor and capital as inputs, with α denoting the share of capital in production. The share of fixed cost in production is given by $1 - \Phi$. Like for labor, the elasticity of substitution over the differentiated goods is time-varying and modeled as in Kimball (1995), where ε_p represents the curvature of the aggregator function. Firms have some degree of monopoly power over setting prices, which are sticky in nominal terms. Price stickiness is modeled following Calvo (1983). The constant probability of not adjusting

prices is given by ξ_p , with prices that do not adjust partially indexed to past inflation, with the extent of indexation given by ι_p .

Government behavior is specified in terms of fiscal and monetary policies. The government levies lump-sum taxes and government spending follows an exogenous path, with some response to the productivity process. In particular, government spending responds by ρ_{ga} to an innovation to total factor productivity. Monetary policy is modeled using an empirical endogenous interest-rate rule which features interest rate smoothing, given by ρ , feedback from inflation, given by r_π , and feedback from output gap, given by r_y . Moreover, there is also some short-run feedback from the change in the output gap, given by $r_{\Delta y}$. It is important to note here that the output gap is the difference between actual output and potential output, where potential output is defined as the output that would prevail under flexible prices and in the absence of the price and wage markup shocks.

The economy is driven by seven fundamental aggregate shocks. The total factor productivity, investment-specific technology, risk premium, exogenous government spending, and monetary policy shocks follow AR(1) processes. The persistence parameters of the shocks are given by ρ_a , ρ_I , ρ_b , ρ_g , and ρ_r and the standard deviations of the innovations by σ_a , σ_I , σ_b , σ_g , and σ_r respectively. The price and wage markup shocks are assumed to follow ARMA (1,1) processes, with ρ_p and ρ_w representing the corresponding AR parameters and μ_p and μ_w the corresponding MA parameters. The standard deviations of the innovations are given by σ_p and σ_w . Finally, the model features deterministic growth driven by labor-augmenting productivity with the quarterly trend growth rate in real GDP given by $\bar{\gamma}$. Similarly, the quarterly steady-state inflation rate is given by $\bar{\pi}$, the steady-state hours worked by \bar{l} , and the steady-state government spending to GDP ratio by g_y .

4.1.1 Estimation

We directly follow Smets and Wouters (2007) in our estimation exercise. We use quarterly U.S. data from 1966:I -2004:IV on log difference of real GDP, real consumption, real investment, real wage, and the GDP deflator, log hours worked, and the federal funds rate. We therefore use seven observables along with seven fundamental shocks. In particular, our estimation exercise does not – for now – feature measurement errors. We follow a standard Bayesian estimation and model comparison procedure for linearized models. All the details can be found in Appendix D.²⁰

²⁰The likelihood function is evaluated using the Kalman filter. We compute the mode of the posterior and then use a random-walk Metropolis algorithm to sample from the posterior distribution. A scaled version of

As in Smets and Wouters (2007), we calibrate a few parameters: δ is set at 0.025, g_y at 0.18, λ_w at 1.5, and ε_p and ε_w at 10. For the rest of the parameters that are estimated, the prior distributions are described in Tables 2 and 3. We directly follow Smets and Wouters (2007) in the priors we pick, except for the price and wage markup shocks. Smets and Wouters (2007) estimate a scaled version of the markup shocks, which is a combination of the true markup shocks and various structural parameters, in particular, the probability of price and wage adjustment. Since our main goal is to conduct a comparative statics exercise on the probability of price and wage adjustment, we estimate the “true” price and wage markup shocks. For this reason, the prior mean of the standard deviation of the price and wage markup shocks are set at a quite high value.

The posterior estimates of the various parameters of the model that features wage but not price indexation are given in Tables 4 and 5.²¹ Since our entire exercise is extremely close to that of Smets and Wouters (2007), the estimates are in line with their results. The only exceptions are the estimates pertaining to the price and wage markup shocks for reasons described above. A point worth emphasizing here is that the policy rule is estimated with a Taylor rule coefficient of $\phi_\pi = 2.07$. This puts us in the parameter region in which price and wage flexibility is stabilizing for demand shocks while destabilizing for supply shocks.

4.1.2 Price-Wage Flexibility: Counterfactual Experiments

With the posterior estimates of the structural parameters and the shocks at hand, we now conduct the following counterfactual experiment: We recover the historical realizations of all the shocks from the estimated model and feed these into the model assuming prices and wages are completely flexible.²² We then simulate the implied counterfactual historical path for annual output growth and compare it with the actual path, while using posterior means as values for all parameters. Panel (a) in Figure 5 reports the results of this exercise. We see that for the bulk of post-WWII history, output growth per year would have been more volatile under flexible prices and wages. This is especially the case in the 1970s although output would have been slightly less volatile in the Volcker disinflation period of early 1980s. Taken together this counterfactual history suggest a standard deviation of annual output growth of 4.43 percent if prices and wages had been flexible relative to what was seen in the

the inverse of the Hessian computed at the mode is used as a proposal density in the random walk Metropolis algorithm. The results we report are based on 2.5 million draws, with one third of the draws burned-in. We assess convergence using multiple chains and trace-plots.

²¹We found this specification to best fit the data using a Bayesian model comparison exercise following the methodology in Geweke (1999).

²²We use smoothed shocks.

data, which corresponds to 2.18 percent. If only prices had been flexible but not wages, the same number is 2.85 percent.

Our theoretical analysis made clear that while nominal rigidities are stabilizing for some shocks, this is not true for all shocks. The same insight carries over to the estimated model. This is made clear in other panels in Figure 5, which show the evolution of annual output growth with and without flexible prices and wages for one shock at a time. Of particular note is that in the case of “demand shocks,” output is typically more stable if prices and wages are flexible. For example, Panel (b) in Figure 5 shows the evolution of output growth if we only feed the monetary policy shock into the model, while shutting down all other shocks. As expected, we see that the monetary policy shock would have no effect on output. As prices and wages become rigid as in the data, however, output starts moving about. What is particularly noteworthy here is that output drops most – as expected – during the Volcker disinflation period in the early 1980s. Thus flexible prices/wages would have contributed to economic stability in that period, that is, the U.S. could have avoided the monetary driven recession altogether which is consistent with the overall picture for aggregate output growth in Panel (a). A similar pattern can be seen for other demand shocks. In particular, we see that risk premium shocks have no effect if there are no nominal frictions while exogenous spending shocks and investment specific shocks have some effect, but of a smaller magnitude than if the model has the nominal rigidities of the extent observed in the data.

Turning to “supply shocks,” we see in Figure 5, Panels (f)-(h), that output growth is in general more volatile if prices/wages are flexible, which is consistent with our theoretical results given the estimated policy rule. We see in particular that in the 1970s output would have been more volatile in the counterfactual analysis, consistent with the view that supply shocks were predominant during that period. The supply shocks in the estimated model are the productivity shock and the price and wage markup shocks as seen in Panels (f)-(h).

While looking at a counterfactual path based on smoothed shocks is instructive, it is also helpful to compute the unconditional standard deviation of output growth in the model, given our estimates of the parameters and various shocks.²³ We do this in Table 6, where we include the results for both the case when only prices are flexible as well as the case when both wages and prices are flexible. The table confirms that we obtain the same results in the extended model as in the analytical exercise and that it holds either when we assume that only prices are flexible or if both wages and prices are flexible. Since our estimates imply a responsive monetary policy (that is, the Taylor coefficient is relatively high), we find

²³Here we report the standard deviation of quarterly output growth.

that had prices/wages been flexible, aggregate volatility would have increased for “supply” shocks, that is, for productivity, price mark-up, and wage mark-up shocks. In contrast, it would have decreased for “demand shocks,” that is, for risk-premium, investment-specific, technology, exogenous spending, and monetary policy shocks. Again, note that with no nominal rigidities, risk premium and monetary policy shocks do not have any real effects at all. These results suggest that the mechanisms we uncovered in the analytical section are robust to extending the model to an estimated medium-scale macro model.

Moreover, Table 6 emphasizes that behind our aggregate result of increased output growth volatility is the feature that the volatility of output growth is particularly sensitive to changes in price/wage stickiness for the three supply shocks.²⁴ These shocks are precisely the ones that lead to greater volatility of output growth when prices/wages become more flexible under the estimated monetary policy reaction function. Their effect dominates the reduction in output growth volatility due to other demand and policy shocks. Since these shocks are at the heart of the quantitative results, it is worth exploring their interpretation in more detail. It is also interesting to conduct some counterfactual experiments with alternative monetary policy rules since the monetary policy reaction function is also an integral part of our analysis.

The Role of Markup Shocks The role of markup shocks in the Smets-Wouter model has come under considerable criticism in recent years. Chari et al. (2009), for example, argue that wage markup shocks are too volatile, and do not have a plausible economic identification/interpretation. It is therefore worth better understanding the role of these shocks for our results. To do so, here we run our counterfactual simulation in the Smets-Wouters model by explicitly eliminating these shocks one at a time and then altogether. In the next section, instead of shutting them down, we then go on to identify these shocks more explicitly.

The bottom part of Table 6 shows the effect on output volatility once we exclude each of the markup shocks from the model. The thought experiment we run is the following: Suppose we shut down one or both of the “questionable” structural shocks and simulate our model again excluding this shock while keeping the rest of the parameters at estimated values. How does the model behave as we increase price and wage flexibility? As the table shows, output volatility increases as prices become perfectly flexible even if both of the markup shocks are

²⁴Note that this does not mean that at the estimated values, the price and wage markup shocks are dominant in explaining output growth variance. Unconditionally, they explain 10% and 15% of the variance respectively. It is just that the change in variance is sensitive to change in nominal flexibility for these shocks.

shut down. Recall that even if both shocks are shut down, there is still an important supply shock in the model, namely technology shock, and this shock is important enough to still generate an overall increase in volatility. If both wage and prices are flexible, however (this is the last line in the table) then output volatility goes down. In other words: under this specification of complete nominal flexibility, technology shocks are not enough to generate an increase in output volatility in the model given the presence of demand shocks. The table reveals, however, that either one of these shocks is enough to generate an increase in output volatility in the model, even if there is complete nominal flexibility. Finally, we can ask the following question, rather than shutting down both markup shocks: how large would they need to be – relative to the baseline estimation – to generate an increase in output volatility if both prices and wages are flexible? In simulating the model we find that the standard deviation of the shock innovations need to be at approximately 15 percent of their estimated values to generate an overall increase in output growth volatility.

While the thought experiments above are instructive, and do suggest that we can even shut down one of the markup shocks (such as the wage markup shock which has been subject to the greatest criticism) completely and maintain the basic overall quantitative result, it can also be somewhat misleading. Why? Because as the table reveals, then if we shut down one of the shocks in the model – even if we think it might be questionable – the model is then not generating the same amount of volatility for output growth. For example, the model only generates 0.84 percent (unconditional) standard deviation in output growth when both markups are shut down relative to 0.98 in the baseline. A better approach might be to re-estimate the model while eliminating or providing better identification of the questionable shocks. By doing so, we ensure that the volatility we see in the data then gets loaded onto some other component in the model. This is the strategy we adopt in the next section. Before doing that, however, we first assess the role of the monetary policy rule next.

Alternative Policy Rules One underlying assumption in our counterfactual examples in this section is that the policy rule remains unchanged even as prices and wages become more flexible. This assumption is less troublesome than one might think at first glance, since if both prices and wages are fully flexible, then the monetary policy rule has no effects, since monetary policy becomes irrelevant. This may matter, however, when we make only prices flexible as we do in some of our experiments. For this reason, we include in Table 7 three alternative policy rules informed by our analytical sections: involving output gap and inflation, output gap growth and inflation, and finally output gap, wage growth, and

inflation.²⁵ In this table, we report results when we simulate the model when the central bank follows such a targeting rule using values for the targeting rule parameters based on the analytical section.²⁶ Overall, the qualitative results are unchanged, output growth volatility again increases under this policy specification as we make only prices flexible (again recall that the monetary policy specification is irrelevant when both wages and prices are flexible).

4.2 Alternative Estimations of Wage and Price Markup Shocks

We now estimate two alternative models suggested in the literature that provide a better identification and interpretation of the wage and price markup shocks, and assess if our major quantitative results continue to hold. We find that our results continue to hold or even strengthen.

4.2.1 Gali-Smets-Wouters Model

A prominent model that explicitly addresses the questionable wage markup shock is that of Gali et al. (2011). Since we do not change the model, we refer the reader to the Gali et al. (2011) paper for a detailed description of the model and in Appendix E we report the log-linearized equilibrium conditions. Briefly, in this model, the wage markup shock in the Smets-Wouters model is decomposed into three different parts by the introduction of a new observable variable, namely unemployment and by allowing for measurement errors in the wage series. The previous wage markup can now be split into a labor supply shock, a measurement error, and again a conventional wage markup shock.

We report the priors and the posterior estimates of the parameters obtained using the same data as in Gali et al. (2011) in Appendix E and focus here on the counterfactual result. Table 8 shows that in this model, the standard deviation of quarterly output growth also goes up when either only prices or both prices and wages become flexible.²⁷ The second part of the table also presents a similar exercise as in Table 6, that is, it asks if output volatility still goes up with nominal flexibility if we shut down the markup shocks. In all cases, output volatility goes up, even if both markup shocks and the labor supply shock are shut down. The reason for this somewhat stronger result than in the baseline model is that in this estimated model, productivity shocks now play a somewhat larger role than before,

²⁵Here, the potential output we use is the output that would prevail in the case of flexible price and wages and the absence of the two markup shocks.

²⁶The rest of the parameter values are fixed at estimated values.

²⁷Again, we report unconditional moments based on our estimated parameter values.

so that even if all other supply shocks are shut down, it remains the case the output growth volatility goes up as nominal rigidities go to zero.

A very appealing feature of this estimated model is that the measurement error takes up a large fraction of the high-frequency variation in the previously estimated wage markup shock, a point also illustrated in Justiniano et al. (2013). Accordingly the standard deviation of the wage markup is more than 100 times smaller in this model than in the baseline Smets-Wouters model, thus rendering it less subject to the Chari et al. (2009) criticism. Interestingly, even if this means that the wage markup shock is much smaller, our results become even stronger and more robust under this specification as the quantitative results above reveal.

4.2.2 deWalque-Smets-Wouters Model

Another approach that reinterprets markup shocks is the one proposed by de Walque et al. (2006). In that model, price-markup variation can be reinterpreted as sector-specific productivity shocks. In particular, that model does not have any price-markup shock but instead features a flexible price sector that is hit with a sector-specific productivity shock. This productivity shock in the flexible price sector then affects the model in a similar manner to the price markup shock in a one-sector model. In Appendix F we provide full details of a two-sector medium scale model in the spirit of de Walque et al. (2006), including the complete set-up and optimization problem of the agents, the non-linear equilibrium conditions, as well as the log-linearized equilibrium conditions. We estimate this model using the same data series as in Smets and Wouters (2007). Appendix F contains more details on the estimation as well as the priors and posterior estimates of the model parameters.

Table 9 shows the results based on our counterfactual experiments in this two-sector model. Again, we see that output volatility goes up as either prices or both prices and wages become fully flexible. We also observe that even if we shut down the labor markup shock, then the result is still maintained for price flexibility. In this case, the only supply shocks in the model are aggregate and sector specific productivity shocks. Output growth volatility does go down, however, without labor markup shocks when both prices and wages are flexible, as shown in Table 6.

5 Conclusion

In this paper, we study the aggregate implications in a DSGE model of increased price and/or wage flexibility. Our analytical results highlight the importance of the source of shocks,

the modeling of monetary policy, and the general equilibrium environment in assessing the aggregate implications of increased price flexibility. In particular, when monetary policy is not responsive enough to inflation, output volatility goes up in the case of demand shocks while output volatility goes up in the case of supply shocks regardless of the monetary policy reaction function. Moreover, welfare can decrease with increased price flexibility for both demand and supply shocks if monetary policy is not very responsive to inflation. We also show several instances where welfare can be lower with increased price/wage flexibility, even when monetary policy is conducted optimally. These cases arise in the face of markup shocks or large negative demand shocks (which drive the economy to a liquidity trap) in a model with price stickiness, and in the face of standard productivity shocks in a model with price and wage stickiness.

In a quantitative exercise using an estimated DSGE model and U.S. data, we find that conditional on the estimated values of the structural parameters and shocks, increased price/wage flexibility would indeed have been destabilizing. This result is maintained in several variations of the popular Smets-Wouters model. The key reason for this conclusion is the important role played by supply shocks, both efficient and inefficient, in the estimated model. For this result to be overturned, we suspect the model would need to be amended in such a way as to give demand shocks a greater role in generating output fluctuations. Further research may very well move the state-of-the-art DSGE models into this direction.

While the following two points are a bit speculative, we believe the mechanism we have uncovered is likely to explain at least two other empirical phenomena. First, our paper may shed some light on why the Great Recession triggered a far smaller drop in output than the U.S. economy experienced during the Great Depression: the Great Recession was associated with a relatively modest decline in inflation, while the Great Depression was characterized by excessive deflation, and the model suggests the former should trigger a smaller drop in output than the latter. Second, our model may shed light on cross-country variation in output volatility. One important factor there may be that in certain countries monetary policy is relatively unstable, which may trigger prices to be more flexible. The model suggests that if certain shocks are driving the business cycle, then this may be one factor in explaining cross-country variations in output volatility.

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6 Tables

Table 1: Illustrative Parameter Values

Parameter	Value	Parameter	Value
β	0.99	σ	1
κ	0.02	θ	10
ρ_j	0.9	$\theta_w = \theta_p$	10
γ	0.7	ϕ_y only	0.125
ν	1	$\phi_\pi; \phi_y$	1.5, 0.2; 0.125, 20

Table 2: Prior Distribution of Structural Parameters

Parameters	Domain	Density	Prior Mean	Prior Stdev
φ	\mathbb{R}	Normal	4.00	1.50
σ_c	\mathbb{R}	Normal	1.50	0.37
h	$[0,1)$	Beta	0.70	0.10
ξ_w	$[0,1)$	Beta	0.50	0.10
σ_l	\mathbb{R}	Normal	2.00	0.75
ξ_p	$[0,1)$	Beta	0.50	0.10
ι_w	$[0,1)$	Beta	0.50	0.15
ι_p	$[0,1)$	Beta	0.50	0.15
ψ	$[0,1)$	Beta	0.50	0.15
Φ	\mathbb{R}	Normal	1.25	0.12
r_π	\mathbb{R}	Normal	1.50	0.25
ρ	$[0,1)$	Beta	0.75	0.10
r_y	\mathbb{R}	Normal	0.12	0.05
$r_{\Delta y}$	\mathbb{R}	Normal	0.12	0.05
$\bar{\pi}$	\mathbb{R}^+	Gamma	0.62	0.10
$100(\beta^{-1} - 1)$	\mathbb{R}^+	Gamma	0.25	0.10
\bar{l}	\mathbb{R}	Normal	0.00	2.00
$\bar{\gamma}$	\mathbb{R}	Normal	0.40	0.10
α	\mathbb{R}	Normal	0.30	0.05

Table 3: Prior Distribution of Shock Processes

Parameters	Domain	Density	Prior Mean	Prior Stdev
ρ_a	$[0,1)$	Beta	0.5	0.2
ρ_b	$[0,1)$	Beta	0.5	0.2
ρ_g	$[0,1)$	Beta	0.5	0.2
ρ_I	$[0,1)$	Beta	0.5	0.2
ρ_r	$[0,1)$	Beta	0.5	0.2
ρ_p	$[0,1)$	Beta	0.5	0.2
ρ_w	$[0,1)$	Beta	0.5	0.2
ρ_{ga}	$[0,1)$	Beta	0.5	0.2
μ_p	$[0,1)$	Beta	0.5	0.2
μ_w	$[0,1)$	Beta	0.5	0.2
σ_a	\mathbb{R}^+	InvG	0.10	0.5
σ_b	\mathbb{R}^+	InvG	0.10	2
σ_g	\mathbb{R}^+	InvG	0.10	2
σ_I	\mathbb{R}^+	InvG	0.10	2
σ_r	\mathbb{R}^+	InvG	0.10	2
σ_p	\mathbb{R}^+	InvG	4.00	4
σ_w	\mathbb{R}^+	InvG	5.00	5

Table 4: Posterior Estimates of Structural Parameters

Parameters	Prior	Posterior	Probability Interval	
	Mean	Mean	90%	
φ	4.00	5.4878	[3.8117	7.1473]
σ_c	1.50	1.3444	[1.1319	1.5553]
h	0.70	0.7173	[0.6469	0.7892]
ξ_w	0.50	0.6184	[0.5182	0.7220]
σ_l	2.00	1.4825	[0.6539	2.2722]
ξ_p	0.50	0.6124	[0.5396	0.6833]
ι_w	0.50	0.6143	[0.4158	0.8182]
ψ	0.50	0.5712	[0.3912	0.7492]
Φ	1.25	1.6149	[1.4869	1.7426]
r_π	1.50	2.0701	[1.7830	2.3554]
ρ	0.75	0.7936	[0.7516	0.8367]
r_y	.125	0.0843	[0.0474	0.1209]
$r_{\Delta y}$.125	0.2169	[0.1699	0.2638]
$\bar{\pi}$.625	0.8310	[0.6115	0.9660]
$100(\beta^{-1} - 1)$	0.25	0.1690	[0.6580	1.0013]
\bar{l}	0.00	-0.0723	[-1.8855	1.7663]
$\bar{\gamma}$	0.40	0.4276	[0.4033	0.4520]
α	0.30	0.1914	[0.1620	0.2203]

Table 5: Posterior Estimates of Shock Processes

Parameters	Prior	Posterior	Probability Interval	
	Mean	Mean	90%	
ρ_a	0.5	0.9563	[0.9376	0.9754]
ρ_b	0.5	0.2041	[0.0651	0.3349]
ρ_g	0.5	0.9751	[0.9614	0.9890]
ρ_I	0.5	0.7149	[0.6202	0.8130]
ρ_r	0.5	0.1730	[0.0592	0.2817]
ρ_p	0.5	0.9050	[0.8441	0.9705]
ρ_w	0.5	0.9733	[0.9570	0.9899]
ρ_{ga}	0.5	0.5196	[0.3714	0.6666]
μ_p	0.5	0.5587	[0.3699	0.7464]
μ_w	0.5	0.8030	[0.7021	0.9055]
σ_a	0.10	0.4568	[0.4107	0.5025]
σ_b	0.10	0.2434	[0.2045	0.2821]
σ_g	0.10	0.5285	[0.4773	0.5782]
σ_I	0.10	0.4520	[0.3704	0.5322]
σ_r	0.10	0.2494	[0.2233	0.2746]
σ_p	4.00	3.8069	[2.0399	5.5395]
σ_w	5.00	14.5539	[5.6942	23.5754]

Table 6: Price and Wage Flexibility Experiment

Shocks	Std Dev of Quarterly Output Growth			
	Baseline	Nominal Stickiness	Flexible Prices	Flexible Prices and Wages
All	0.9848		2.1349	3.0881
Technology	0.4037		0.6292	0.5291
Risk-premium	0.4427		0.3656	0.0000
Govt-spending	0.5036		0.4748	0.4409
Investment-specific	0.3231		0.2555	0.2629
Monetary policy	0.0592		0.0484	0.0000
Price markup	0.3157		1.8481	1.2099
Wage markup	0.3870		0.5653	2.7440
All except price markup	0.9328		1.0687	2.8412
All except wage markup	0.9056		2.0587	1.4168
All except both markup	0.8488		0.9070	0.7372

Table 7: Effect of Different Targeting Rules

Shocks	Std Dev of Quarterly Output Growth			
	Baseline	Nominal Stickiness	Flexible Prices	Flexible Prices and Wages
Targeting rule with inflation and output gap				
All	2.9780		17.7679	3.0881
All except both markup	0.9748		1.8649	0.7372
Targeting rule with inflation and output gap growth				
All	1.6855		14.7131	3.0881
All except both markup	0.8763		1.7010	0.7372
Targeting rule with inflation, output gap, and wage growth				
All	2.2391		14.9663	3.0881
All except both markup	0.8906		1.6841	0.7372

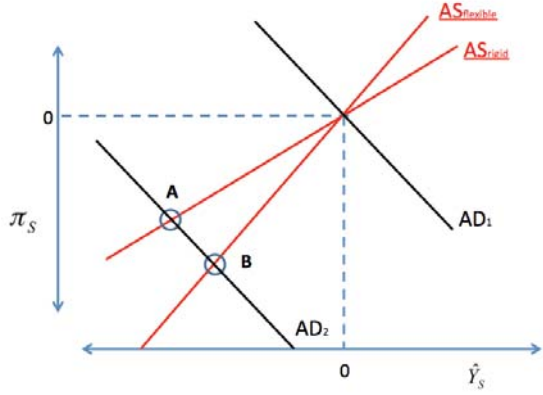
Table 8: Price and Wage Flexibility Experiment in the Gali, Smets and Wouters Model

Shocks	Std Dev of Quarterly Output Growth		
	Baseline Nominal Stickiness	Flexible Prices	Flexible Prices and Wages
All	0.9523	4.5469	9.5981
All except price markup	0.9490	0.9963	2.8466
All except both markup	0.9311	0.9757	1.0013
All except price markup and labor supply	0.9322	0.9791	2.8193
All except both markup and labor supply	0.9139	0.9581	0.9207

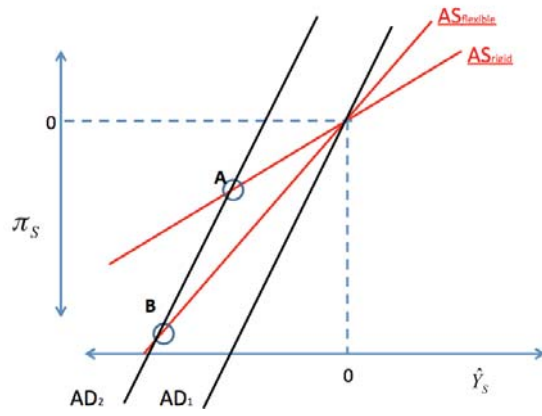
Table 9: Price and Wage Flexibility Experiment in the Two-sector Model

Shocks	Std Dev of Quarterly Output Growth		
	Baseline Nominal Stickiness	Flexible Prices	Flexible Prices and Wages
All	1.1388	1.2501	2.8683
All except wage markup	1.0932	1.1459	1.0435

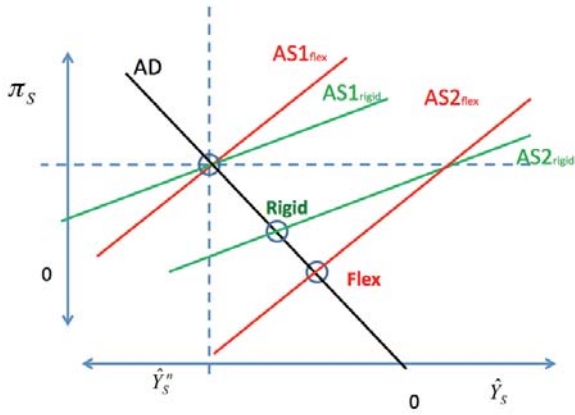
7 Figures



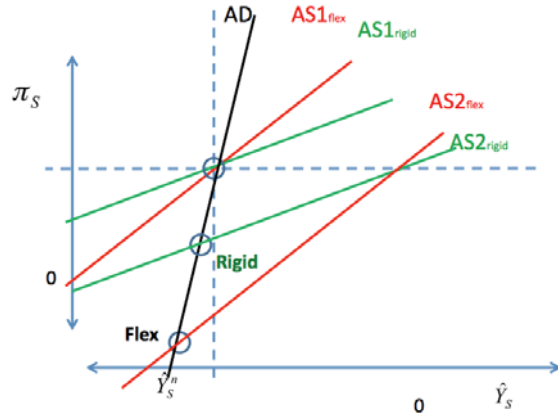
(a) Responsive Monetary Policy, Demand Shock



(b) Non-Responsive Monetary Policy, Demand Shock



(c) Responsive Monetary Policy, Supply Shock



(d) Non-Responsive Monetary Policy, Supply Shock

Figure 1: Effect of Price Flexibility under Responsive and Non-Responsive Monetary Policy for Demand and Supply Shocks

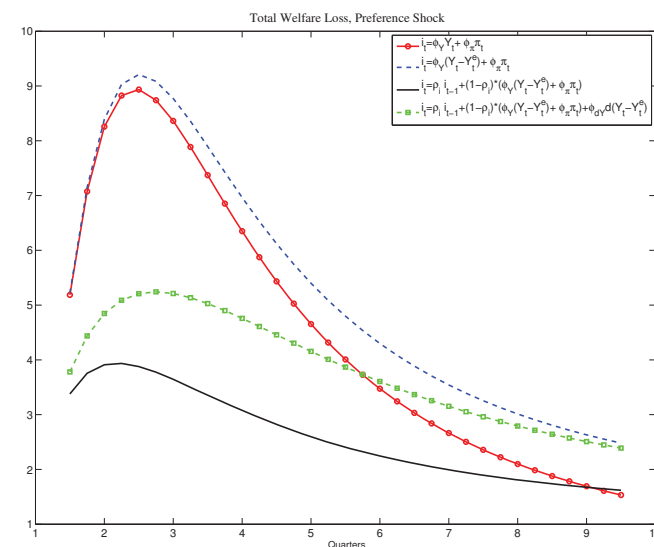
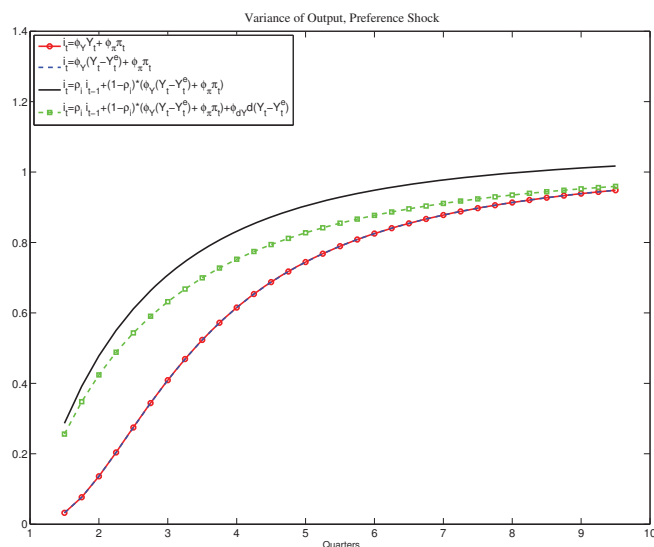
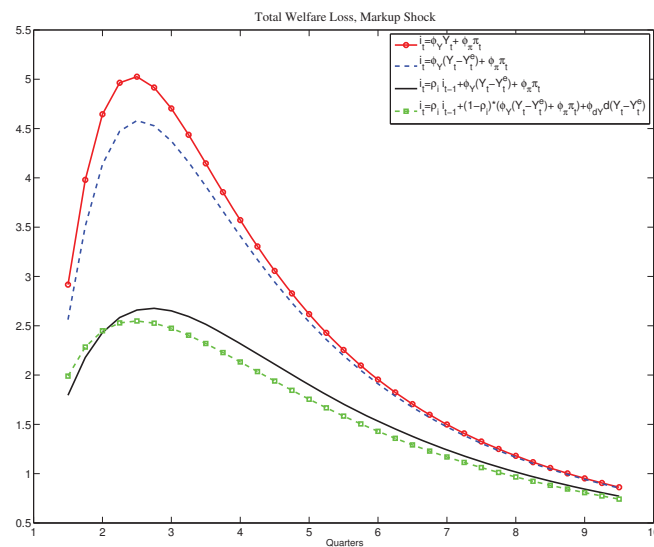
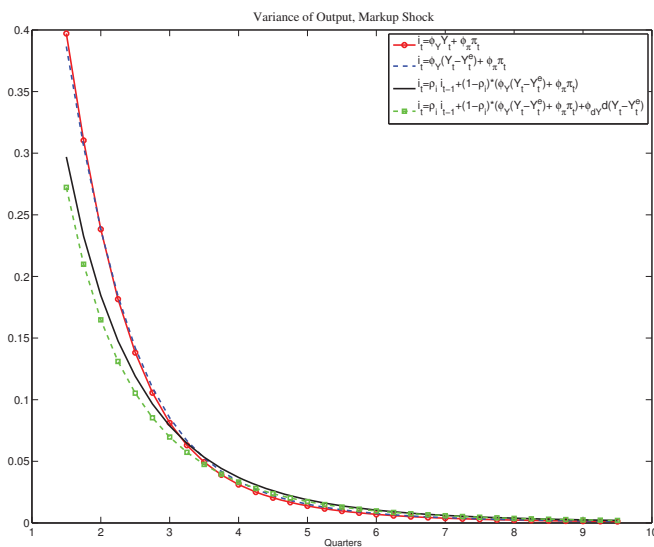
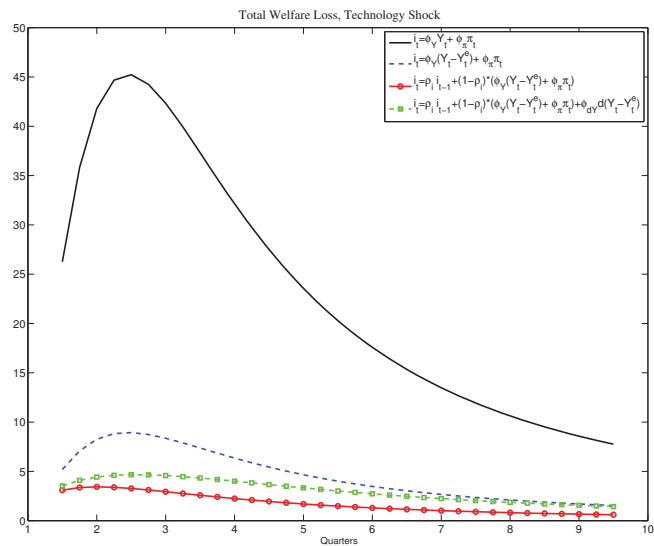
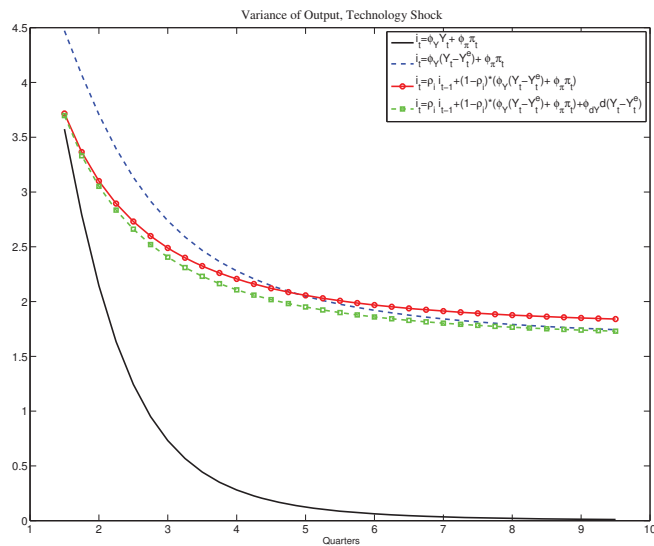


Figure 2: Variance of Output and Welfare under Alternative Policy Rules

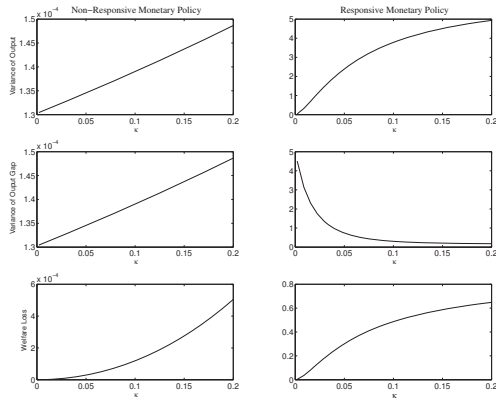


Figure 3: Variance of Output, and Welfare Loss as a Function of Flexibility with Technology Shocks

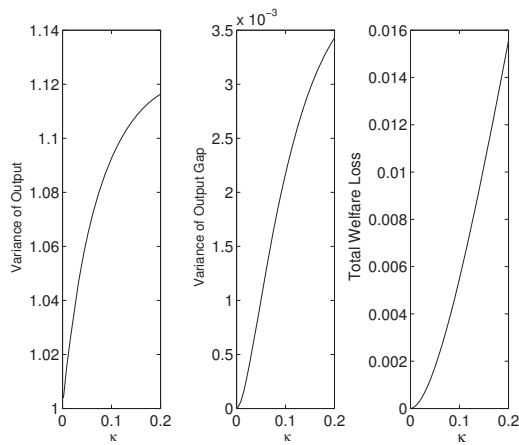
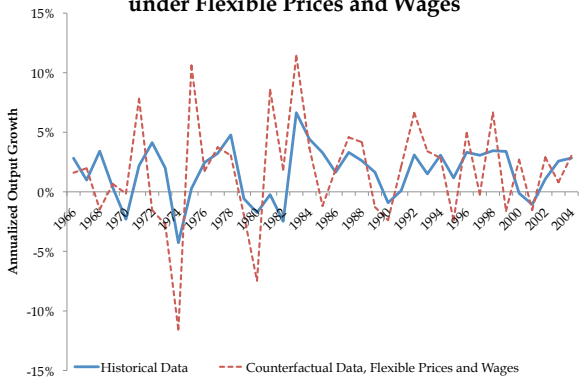


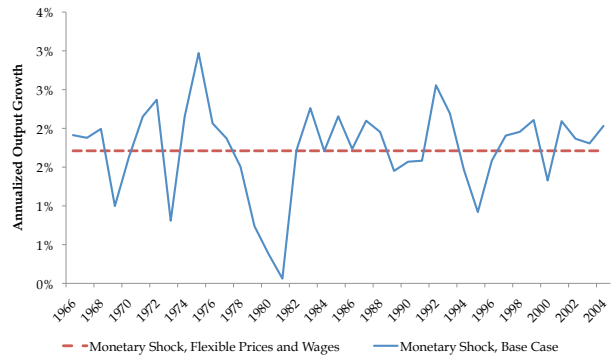
Figure 4: Variance of Output and Welfare Loss under Discretion as a Function of Flexibility with Technology Shocks

Actual and Counterfactual Output Growth under Flexible Prices and Wages



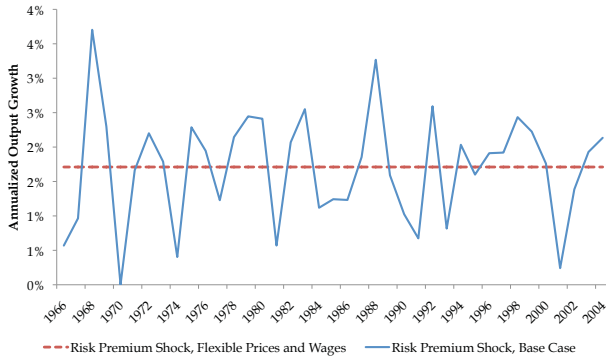
(a)

Output Growth due to Monetary Shocks under Flexible Prices and Wages



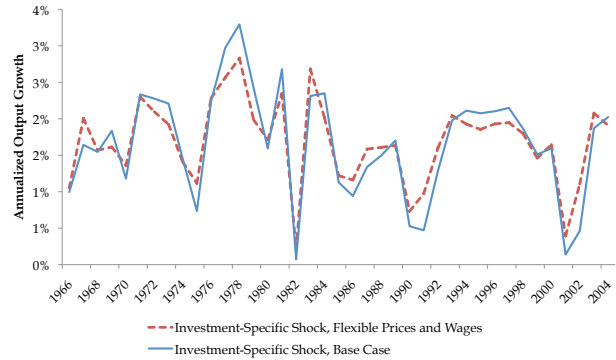
(b)

Output Growth due to Risk Premium Shocks under Flexible Prices and Wages



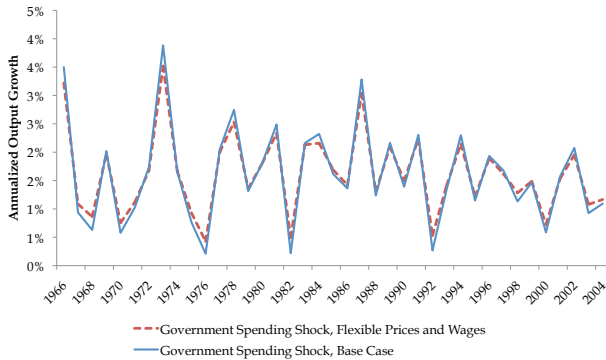
(c)

Output Growth due to Investment-Specific Shocks under Flexible Prices and Wages



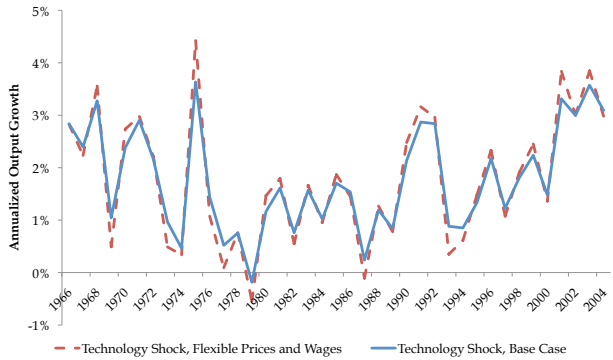
(d)

Output Growth due to Government Spending Shocks under Flexible Prices and Wages



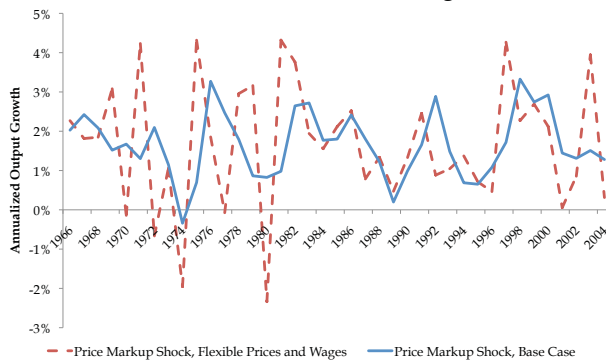
(e)

Output Growth due to Technology Shocks under Flexible Prices and Wages



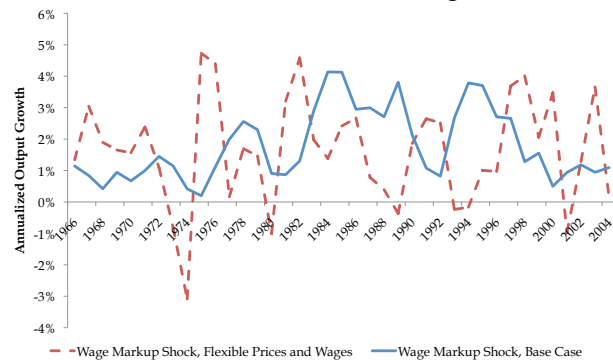
(f)

Output Growth due to Price Markup Shocks under Flexible Prices and Wages



(g)

Output Growth due to Wage Markup Shocks under Flexible Prices and Wages



(h)

Figure 5: Counterfactual and Actual Output Growth, All Shocks and by Individual Shocks