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Imperfect Credibility, Sticky Wages, and Welfare*

Ricardo Nunes† Donghyun Park‡ Luca Rondina§

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Abstract

This paper studies optimal monetary policy under imperfect credibility in a New Keynesian model with staggered price and wage setting. In our imperfect credibility framework, the central bank commits to a policy plan but occasionally reneges on past promises with a given common knowledge probability. We find that the welfare gains from increasing credibility are approximately linear on the initial credibility level. We also find that the output-inflation stabilisation trade-off is nonmonotonic as higher credibility does not always reduce output volatility. The variance decomposition shows that wage markup shocks are the main driver of economic fluctuations and that these shocks are better contained, even in relative terms, when credibility is high. We then show that the degree of credibility impacts the effect of wage flexibility on welfare. When credibility is low, monetary policy is less potent and the economy can experience a feedback loop between wage volatility and price volatility. We show, though, that once wage markup shocks are taken into account, wage flexibility is usually welfare improving.

JEL classification: E24, E52, E58, E61.

Keywords: Imperfect Credibility, Monetary Policy, Wage Flexibility.

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†University of Surrey and CIMS: ricardo.nunes@surrey.ac.uk
‡University of Surrey: d.park@surrey.ac.uk
§Corresponding author. University of Sussex: l.rondina@sussex.ac.uk
1 Introduction

In seminal contributions, Kydland and Prescott (1977) and Barro and Gordon (1983) showed that optimal policy plans can be subject to time-inconsistency. In a model with rational forward-looking agents, the optimal policy plan prescribes that a central bank should manage expectations of future outcomes. Nevertheless, honouring past promises becomes sub-optimal from the perspective of a future central bank, hence the time-inconsistency of the originally formulated policy plan.

In order to address this issue, the literature has focused on two main models of central bank behaviour: commitment and discretion. Under commitment, the policymaker has access to a commitment technology that allows her to fully deliver on past promises at any point in the future, therefore bypassing the time-inconsistency problem. The temptation to renege is still present but the planner does not deviate from previously announced plans. In contrast, under discretion the policymaker can never fulfil a previous promise and, instead, always chooses her actions based on current circumstances. Discretion is therefore time-consistent by construction.

Despite the valuable insights produced using either framework, both models of optimal policy contrast with some stylised facts. For instance, it is impossible to commit based on unforeseen contingencies, also the composition of policy committees changes over time and so does the understanding of economic models and data, which determines that policy strategies must be reformulated and previous commitments may be occasionally reneged on. On the other hand, central banks actively try to influence expectations through policy statements and forward guidance, which suggests that central banks retain some imperfect credibility to announce future policy actions and fulfil past promises.

In this paper we consider a monetary policy setting that spans the limiting cases of full commitment and full discretion. This is known in the literature as loose commitment or quasi commitment. Under loose commitment, the policymaker can credibly commit to an announced policy plan and honour past promises; however, with an exogenous probability she will renege on previous plans and reoptimize. The central bank is aware that it may be given the opportunity to revise its plans later on, and formulates optimal policy accordingly. Moreover, the probability of reneging is common knowledge to all agents, which internalise this information when forming expectations. As a result, the credibility of the monetary authority is imperfect.

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1See Roberds (1987), Schaumburg and Tambalotti (2007), and Debortoli and Nunes (2010).
2This approach to staggered optimal policy is analogous to the Calvo staggered pricing for firms. Plans are “sticky” in the sense that they cannot be reset in every period with a given probability.
We study optimal monetary policy under imperfect credibility in a baseline New Keynesian model with sticky prices and sticky wages. This canonical model has the key advantage that analytical expressions for welfare can be used, which provides a more transparent and rigorous framework for optimal policy evaluation. In addition, the presence of both price and wage stickiness means that this model retains key frictions for evaluating the trade-offs of optimal monetary policy and the effects of wage flexibility on welfare.\(^3\) In this paper, we argue that the interplay between these two elements of the model, imperfect credibility and wage stickiness, is key in providing a comprehensive understanding of welfare losses.

The loose commitment paradigm allows us to investigate interesting normative and positive aspects of monetary policy and credibility. On the normative side, the relationship between credibility and welfare can be studied and the welfare gains from increasing commitment can be measured. On the positive side, solving the optimal policy under loose commitment allows us to evaluate the transmission of monetary policy under different credibility levels and the associated business cycle properties.

After examining the main features of the model, the paper examines the debate of whether wage flexibility is welfare improving. The model features several frictions and shocks; by the theory of the second best, it is not necessarily the case that decreasing the degree of wage rigidity leads to higher welfare. In fact, Galí (2013) and Galí and Monacelli (2016) discuss that increasing wage flexibility may reduce welfare. We show that the degree of credibility can be important in this discussion. If credibility is low, monetary policy may not counteract the potential feedback loop between wage and price inflation. Consequently, when monetary policy is not very credible, wage flexibility can be welfare detrimental for a wider range of cases. However, we also incorporate wage markup shocks in the model. These shocks are important in the empirical literature, and we find that wage flexibility is key to dampen the welfare losses of wage markup shocks.

This paper is related to the literature on optimal monetary policy and loose commitment settings.\(^4\) In particular, this work is related to Schaumburg and Tambalotti

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\(^3\)This model was first introduced in Erceg et al. (2000). Galí (2015) provides an extensive textbook analysis, and for instance Galí and Monacelli (2016) and Debortoli et al. (2019) provide recent applications.

\(^4\)Optimal monetary policy design and formalisation of the planner’s problem follows the seminal work of Clarida et al. (1999) as well as Galí (2015) and Woodford (2003). Solution methods and properties of linear-quadratic optimal policy frameworks are discussed in Currie and Levine (1993),
(2007) and Debortoli et al. (2014). Unlike the latter, we use a microfounded loss function, which is key to have an accurate computation of welfare. Unlike Schaumburg and Tambalotti (2007), we consider a model with sticky prices and sticky wages, which introduces additional trade-offs for monetary policy. Our framework allows us to check accurately the effects of wage rigidities on welfare. On this front we extend Galí (2013) by incorporating additional shocks and examining imperfect credibility settings.

The paper is organised as follows. Section 2 describes the model. Section 3 investigates the relationship between central bank credibility and welfare losses. Section 4 examines the transmission mechanism and business cycle properties under different degrees of commitment. Section 5 examines the effects of wage rigidities on welfare. Section 6 concludes.

2 The model

In this section, we introduce the main features and equations that characterise the model. We first characterise the non-policy block of the model. The crucial assumption in this framework is the co-existence of staggered price and wage setting, which creates two important sources of nominal rigidities. At the end of this section, we describe the imperfect credibility framework.

2.1 Households

A representative household consumes a composite good $C_t$ and supplies differentiated labour services. In particular, the representative household consists of a continuum of members (workers) indexed by $j \in [0, 1]$, who specialise in a specific type of labour that is supplied monopolistically.\footnote{Söderlind (1999), Debortoli and Nunes (2006), Dennis (2007), and Benigno and Woodford (2012), among others.}

Differentiated labour services create a wage markup over the equilibrium wage that would prevail in the case of homogeneous labour. This is reflected in a wedge $\mathcal{M}_{w,t}$ between the real wage and the marginal rate of substitution between consumption and labour supply, as shown by

$$\frac{W_t}{P_t} = \mathcal{M}_{w,t} MRS_t,$$

where $W_t$ is the nominal wage, $P_t$ is the aggregate price level, and $MRS_t$ denotes the

$\text{Söderlind (1999), Debortoli and Nunes (2006), Dennis (2007), and Benigno and Woodford (2012), among others.}$

$\text{An equivalent framework consists of a continuum of unions that set the wage, each representing a set of specialised workers.}$
marginal rate of substitution.\(^6\)

An additional source of inefficiency comes from wage staggering. Every period only a fraction \((1 - \theta_w)\) of workers is allowed to renegotiate their nominal wage to its optimal level \(W_t^*\). Therefore, whenever workers have an opportunity to reset their nominal wage, they choose \(W_t^*\) in order to maximise their expected future flows of discounted utility.

Moreover, the desired wage markup \(\mathcal{M}_{w,t}^n\) is time-varying with steady state level \(\mathcal{M}_w \equiv \frac{\epsilon_w}{\epsilon_{w-1}}\). The first order optimality condition for \(W_t^*\) is

\[
\sum_{k=0}^{\infty} (\beta \theta_w)^k \mathbb{E}_t \left[ N_{t+k|t} Z_{t+k} C_t^{\epsilon \sigma} \left( \frac{W_t^*}{P_{t+k}} - \mathcal{M}_{w,t+k}^n MRS_{t+k|t} \right) \right] = 0, \tag{1}
\]

where \(N_{t+k|t} = \left( \frac{W_t^*}{W_{t+k}} \right)^{-\epsilon_w} N_{t+k}\) is labour demand in period \(t + k\) for workers who last reset their wage in period \(t\), and \(Z_t\) is a preference (demand) shock that follows an exogenous AR(1) process

\[
z_t = \rho_z z_{t-1} + \varepsilon_{z,t}
\]

with \(z_t \equiv \log Z_t\).\(^7\)

As standard in the literature, the wage setting equation (1) can be log-linearised around a zero inflation steady state

\[
\pi_t^w = \beta \mathbb{E}_t \left[ \pi_{t+1}^w \right] - \lambda_w (\hat{\mu}_t^w - \hat{\mu}_{w,n}^w), \tag{2}
\]

where \(\pi_t^w\) is nominal wage inflation, \(\lambda_w \equiv \frac{(1 - \theta_w)(1 - \beta \theta_w)}{\theta_w (1 + \epsilon_w \rho)}\), \(\hat{\mu}_t^w \equiv \mu_t^w - \mu^w\) is the deviation of the (log) average wage markup \(\mu_t^w\) from its steady state level \(\mu^w \equiv \log \mathcal{M}_w\), and \(\hat{\mu}_{w,n}^w \equiv \mu_{w,n}^w - \mu^w\) is the deviation of the (log) desired wage markup \(\mu_{w,n}^w \equiv \log \mathcal{M}_{w,t}^n\) from steady state.

### 2.2 Firms

The supply side of the economy is populated by a continuum of firms that produce differentiated goods. Each firm, indexed by \(i \in [0, 1]\), is endowed with the production function

\[
Y_i(i) = A_i N_i(i)^{1-\alpha},
\]

\(^6\)The steady-state deviation from the efficient allocation can be corrected with the introduction of an appropriate subsidy.

\(^7\)The parameters are described in Table 1.
where $A_t$ represents technology that follows an exogenous autoregressive process

$$a_t = \rho_a a_{t-1} + \varepsilon_{a,t}$$

with $a_t \equiv \log A_t$. Each firm aggregates as inputs the differentiated labour types supplied by workers according to

$$N_t(i) \equiv \left( \int_0^1 N_t(i,j)^{\frac{\varepsilon_w-1}{\varepsilon_w}} dj \right)^{\frac{\varepsilon_w}{\varepsilon_w-1}}.$$

Differentiated goods and monopolistic competition in the goods market implies that each firm $i$ can set its own price to maximise profits. However, each period only a fraction $(1 - \theta_p)$ is allowed to readjust their prices, leaving the remaining $\theta_p$ firms with their previously set price. Similarly to the wage setting problem for workers, when a firm has been given the opportunity to reset its price, it has to take into account the expected future profits discounted by the probability of not being able to reoptimise again. Hence, the optimal price $P^*_t$ is set according to the optimality condition

$$\sum_{k=0}^{\infty} \theta_{p,t} \mathbb{E}_t \left[ \Lambda_{t,t+k} Y_{t+k|t} \frac{P^*_t - M^n_{p,t+k} C'_{t+k}(Y_{t+k|t})}{\hat{P}_t+k} \right] = 0, \quad (3)$$

where $\Lambda_{t,t+k}$ is the stochastic discount factor, $Y_{t+k|t} = \left( \frac{P^*_t}{\hat{P}_t+k} \right)^{-\varepsilon_p} C_{t+k}$ is the demand in period $t+k$ for those firms that last reset their price in period $t$, $C'(\cdot)$ is the marginal cost, and $M^n_{p,t}$ is a time-varying desired price markup with steady state level $M_p \equiv \frac{\varepsilon_p}{\varepsilon_p-1}$.

The above optimality condition (3) can be log-linearised around a zero steady state inflation to obtain an equation in terms of price inflation $\pi^p_t$, deviations of the (log) average markup from its steady state level $\tilde{\mu}_t^p \equiv \mu_t^p - \mu^p$, and deviations of the (log) desired markup $\tilde{\mu}_t^{p,n} \equiv \mu_t^{p,n} - \mu^p$, i.e.

$$\pi_t^p = \beta \mathbb{E}_t \left[ \pi_{t+1}^p \right] - \lambda_p (\tilde{\mu}_t^p - \tilde{\mu}_t^{p,n}), \quad (4)$$

where $\lambda_p \equiv \frac{(1-\theta_p)(1-\beta \theta_p)}{\theta_p} \frac{1-\alpha}{1-\alpha+\alpha \theta_p}$.

### 2.3 Equilibrium

The non-policy block of the model is completed by adding two additional equations. The first equation is an identity that relates real wage gap growth to wage inflation,
price inflation, and changes in the natural real wage, i.e.

\[ \tilde{\omega}_t \equiv \tilde{\omega}_{t-1} + \pi^w_t - \pi^p_t - \Delta\omega^a_t, \]  

(5)

where \( \tilde{\omega}_t \) is the real wage gap and \( \Delta\omega^a_t = \phi_{\omega a} \Delta a_t \) denotes real wage growth in the absence of sticky prices and wages and with desired price and wage markups at their steady state.\(^8\)

The second equation is a dynamic IS equation. It describes the inter-temporal optimal allocation of households and it is obtained by combining the Euler equation with the market clearing condition on the goods market. Its log-linearised version is

\[ \tilde{y}_t = E_t [\tilde{y}_{t+1} - \frac{1}{\sigma} (i_t - E_t [\pi^p_{t+1}] - r^n_t)], \]

(6)

where \( \tilde{y}_t \equiv y_t - y^e_t \) is the (welfare-relevant) output gap with \( y^e_t \) denoting the (log) efficient level of output and \( r^n_t = -\log \beta - \sigma (1 - \rho_a) \phi_{ya} a_t + (1 - \rho_z) z_t \) is the natural real interest rate consistent with the efficient level of output.\(^9\)

Finally, it is useful to rearrange the price and wage inflation curves in terms of real wage gap and output gap. Deviations of average markups from steady state counterparts can be rewritten as

\[ \hat{\mu}^p_t = -\frac{\alpha}{1 - \alpha} \tilde{y}_t - \tilde{\omega}_t, \]

\[ \hat{\mu}^w_t = \tilde{\omega}_t - \left( \sigma + \frac{\varphi}{1 - \alpha} \right) \tilde{y}_t, \]

which can be substituted into (2) and (4) to obtain

\[ \pi^p_t = \beta E_t [\pi^p_{t+1}] + \kappa_p \tilde{y}_t + \lambda_p \tilde{\omega}_t + u^p_t, \]

(7)

\[ \pi^w_t = \beta E_t [\pi^w_{t+1}] + \kappa_w \tilde{y}_t - \lambda_w \tilde{\omega}_t + u^w_t, \]

(8)

where \( \kappa_p \equiv \frac{\alpha}{1 - \alpha} \lambda_p, \) \( \kappa_w \equiv (\sigma + \frac{\varphi}{1 - \alpha}) \lambda_w, \) \( u^p_t \equiv \lambda_p \hat{\mu}^{p,n}_t \) is a price cost-push shock, and \( u^w_t \equiv \lambda_w \hat{\mu}^{w,n}_t \) is a wage markup shock. The latter two shocks follow an exogenous

\(^8\)\( \phi_{\omega a} \) is a composite parameter defined as \( \phi_{\omega a} \equiv \frac{1 - \alpha \phi_{ya}}{1 - \alpha}, \) where \( \phi_{ya} \equiv \frac{1 + \varphi}{\sigma (1 - \alpha) + \varphi + \alpha}. \)

\(^9\)The preference shock \( z_t \) enters the dynamic IS equation (6) only. Given that monetary policy is optimal, the policymaker can perfectly offset preference shocks via movements in the nominal interest rate. As a result, these shocks do not influence welfare-relevant variables, i.e. price inflation, wage inflation, and output gap. Also note that the natural level of output coincides with its efficient counterpart if desired price and wage markups are identical to their steady state (\( M^a_{p,t} = M_p \) and \( M^a_{w,t} = M_w \)).
AR(1) process

\[ u_t^p = \rho_u u_{t-1}^p + \varepsilon_{p,t}, \]

\[ u_t^w = \rho_w u_{t-1}^w + \varepsilon_{w,t}. \]

The non-policy block is therefore entirely described by equations (5), (6), (7), and (8). The model is parameterised following Galí (2015) and the standard deviations of the exogenous shock processes are calibrated to match those in Smets and Wouters (2007). Values are reported in Table 1.

**Table 1: Parameters and shocks standard deviations**

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount factor</td>
<td>( \beta )</td>
<td>0.99</td>
</tr>
<tr>
<td>Output elasticity of labour</td>
<td>( \alpha )</td>
<td>0.25</td>
</tr>
<tr>
<td>Risk aversion</td>
<td>( \sigma )</td>
<td>1</td>
</tr>
<tr>
<td>Frisch elasticity of labour supply</td>
<td>( \varphi )</td>
<td>5</td>
</tr>
<tr>
<td>Elasticity of substitution between goods</td>
<td>( \epsilon_p )</td>
<td>9</td>
</tr>
<tr>
<td>Elasticity of substitution between labour varieties</td>
<td>( \epsilon_w )</td>
<td>4.5</td>
</tr>
<tr>
<td>Price stickiness</td>
<td>( \theta_p )</td>
<td>0.75</td>
</tr>
<tr>
<td>Wage stickiness</td>
<td>( \theta_w )</td>
<td>0.75</td>
</tr>
<tr>
<td>Price cost-push shock autoregressive parameter</td>
<td>( \rho_u )</td>
<td>0.8</td>
</tr>
<tr>
<td>Wage markup shock autoregressive parameter</td>
<td>( \rho_w )</td>
<td>0.8</td>
</tr>
<tr>
<td>Technology shock autoregressive parameter</td>
<td>( \rho_a )</td>
<td>0.9</td>
</tr>
<tr>
<td>Preference shock autoregressive parameter</td>
<td>( \rho_z )</td>
<td>0.5</td>
</tr>
<tr>
<td>s.d. price cost-push shock innovation</td>
<td>( \sigma_{\varepsilon_p} )</td>
<td>0.0895</td>
</tr>
<tr>
<td>s.d. wage markup shock innovation</td>
<td>( \sigma_{\varepsilon_w} )</td>
<td>0.1536</td>
</tr>
<tr>
<td>s.d. technology shock innovation</td>
<td>( \sigma_{\varepsilon_a} )</td>
<td>0.6282</td>
</tr>
<tr>
<td>s.d. preference shock innovation</td>
<td>( \sigma_{\varepsilon_z} )</td>
<td>0.2113</td>
</tr>
</tbody>
</table>

*Notes: The table shows the values for structural parameters and standard deviations of the shock processes. The values for structural parameters follow Galí (2015). Standard deviations of innovations to shock processes are calibrated to match Smets and Wouters (2007). The cost-push and wage markup shock processes are adapted to match the ARMA(1,1) processes in Smets and Wouters (2007).*

2.4 **Optimal policy under imperfect credibility**

The presence of monopolistic competition in the labour and goods markets, coupled with staggering wage and price setting, creates a set of possible equilibrium allocations that are different from the efficient allocation that would prevail in the absence of sticky
prices and wages. This gives a role to the monetary authority to select one of these possible equilibria in order to minimise the distortions.

As shown by Galí (2015), in a simple New Keynesian framework such as the one considered here, an objective function for the social planner can be derived directly from the welfare of maximising agents. Up to a second order approximation, welfare losses relative to an efficient steady state with zero price and wage inflation can be represented by

\[ L = \frac{1}{2} \mathbb{E}_{t-1} \sum_{t=0}^{\infty} \beta^t \left\{ \psi_y (\tilde{y}_t)^2 + \psi_p (\pi^p_t)^2 + \psi_w (\pi^w_t)^2 \right\}, \tag{9} \]

where \( \psi_y \equiv (\sigma + \frac{\bar{\epsilon} + \alpha}{1 - \alpha}) \), \( \psi_p \equiv \frac{\bar{\epsilon}_p}{\lambda_p} \), and \( \psi_w \equiv \frac{\bar{\epsilon}_w (1 - \alpha)}{\lambda_w} \).

The weights attached to deviations of endogenous variables from their targets are a function of the structural parameters. In particular, the relative importance of price and wage inflation deviations in the loss function is determined by the relative degree of price and wage stickiness, \( \lambda_p(\theta_p) \) and \( \lambda_w(\theta_w) \), along with the magnitude of steady state markups, \( M_p(\epsilon_p) \) and \( M_w(\epsilon_w) \). For instance, a higher degree of price stickiness (higher \( \theta_p \) thus lower \( \lambda_p \)) implies a greater price dispersion and distortions, while lower markups (lower \( M_p \) due to higher \( \epsilon_p \)) amplify an effect on the dispersion in the quantities of differentiated goods consumed of any given price dispersion. Therefore, even small deviations of price inflation from target result in large deviations from the efficient steady state and thus larger welfare costs.

The formulation of cost-push and wage markup shocks in our model follows closely Galí (2015). In that case the welfare loss function given by (9) is appropriate as the output-gap takes into account these shocks (or the lack thereof). Related to this issue, there is a debate in the literature about the precise way that price cost-push and wage markup shocks enter the model, for instance that different formulations lead to the same linear equations and whether these shocks are inefficient.\(^{10}\) Given this debate, later in the paper we will also show that the results are robust to a calibration where cost-push shocks are removed and the standard deviation of wage markup shocks is reduced.

We consider a benevolent planner that operates under loose commitment. The central bank sets optimal plans and commits to future allocations but may occasionally renege on past promises and readjust plans with an exogenous positive probability. The private sector is aware of this probability and forms expectations consistently, which renders promises on future allocations as imperfectly credible.

\(^{10}\)Several analysis and results can be found in Chari et al. (2009), Galí et al. (2012), Justiniano et al. (2013), and Debortoli et al. (2019).
Formally, whether the planner keeps or reneges on past promises is driven by the realisation of a two-state i.i.d. stochastic process \( \{ \eta_t \}_{t=0}^{\infty} \) which every period takes the values of 1 with probability \( \gamma \), or 0 with probability \( 1 - \gamma \). If \( \eta_t = 1 \), the planner in period \( t \) honours past promises and does not revise its plan for future allocations. If \( \eta_t = 0 \), the planner in period \( t \) reneges on the previously announced plan and chooses allocations based on a new state-contingent plan which is announced to the public. This setting nests the limiting cases of full commitment and full discretion as special cases when \( \gamma = 1 \) and \( \gamma = 0 \), respectively.

The policymaker solves the following minimisation problem:

\[
L_\gamma (x_{-1}) = \min_{\{ \tilde{y}_t, \pi^p_t, \pi^w_t, \bar{\omega}_t, a_t \}_{t=0}^{\infty}} \mathbb{E}_{-1} \sum_{t=0}^{\infty} (\beta \gamma)^t \left[ \frac{1}{2} \{ \psi_y(\tilde{y}_t)^2 + \psi_p(\pi^p_t)^2 + \psi_w(\pi^w_t)^2 \} + \beta (1 - \gamma) L_\gamma (x_t) \right]
\]

s.t. \[
\pi^p_t = \beta \mathbb{E}_t [\pi^p_{t+1}] + \kappa_p \tilde{y}_t + \lambda_p \bar{\omega}_t + u^p_t \quad \forall t \geq 0,
\]

\[
\pi^w_t = \beta \mathbb{E}_t [\pi^w_{t+1}] + \kappa_w \tilde{y}_t - \lambda_w \bar{\omega}_t + u^w_t \quad \forall t \geq 0,
\]

\[
\bar{\omega}_t = \bar{\omega}_{t-1} + \pi^p_t - \pi^w_t - \Delta \omega^w_t \quad \forall t \geq 0,
\]

\[
\tilde{y}_t = \mathbb{E}_t [\tilde{y}_{t+1}] - \frac{1}{\sigma} (i_t - \mathbb{E}_t [\pi^p_{t+1}] - r^w_t) \quad \forall t \geq 0,
\]

where \( L_\gamma (x_t) \) denotes the welfare loss associated to a degree of commitment \( \gamma \) and \( x_t \equiv (u^p_t, u^w_t, a_t, z_t, \bar{\omega}_t) \) is a vector of state variables. \( \mathbb{E}_t \) denotes the usual rational expectations operator and \( \mathbb{E}^\eta_t \) denotes the expectation operator which takes into account the possibility of reoptimisation. For instance, price inflation expectations are defined by \( \mathbb{E}^\eta_t [\pi^p_{t+1}] \equiv \gamma \mathbb{E}_t [\pi^p_{t+1} | \eta_{t+1} = 1] + (1 - \gamma) \mathbb{E}_t [\pi^p_{t+1} | \eta_{t+1} = 0] \). The solution to the above minimisation problem is a set of state-contingent decision rules.\(^{11}\)

### 3 Welfare and credibility

Due to the ability to credibly commit to announced plans, the full commitment planner can manage expectations and spread the negative impact of exogenous shocks over several periods. On the contrary, the discretionary planner is unable to do so as she only has control over contemporaneous variables. As a result, the full commitment policy delivers the best outcome with welfare losses at their minimum, whereas the discretionary policy attains the worst outcome with welfare losses at their maximum. An interesting question is what are the welfare losses for intermediate levels of credibility. Can modest levels of credibility achieve most of the full commitment welfare gains? How costly is

\(^{11}\)Further details on setting the minimisation problem and on the solution method can be found, for instance, in Debortoli and Nunes (2010) and Debortoli et al. (2014).
to lose credibility?

In this section, we compute welfare associated with a degree of commitment \( \gamma \in [0, 1] \) and compare it with welfare in the limiting cases of full commitment and discretion.\(^{12}\) We report welfare gains of imperfect credibility as a fraction of the total gains from commitment. In other words, for an imperfectly credible policymaker with probability of remaining committed \( \gamma \), the relative welfare gains are reported as \( (L_0 - L_\gamma) / (L_0 - L_1)\).\(^{13}\)

Figure 1 shows how relative welfare gains change with the probability of commitment \( \gamma \). Starting from discretion, \( \gamma = 0 \), the welfare gains increase with the degree of commitment until full commitment is achieved, \( \gamma = 1 \). Higher probabilities of commitment translate into a more efficient management of output gap and inflation expectations, which contributes to keep welfare-relevant variables closer to their target.

Figure 1 also suggests that the marginal gain from increasing commitment is largely independent from the initial credibility level. Since the relative welfare gains increase with the probability of commitment at an almost linear pace, any increase (decrease) in credibility is associated with a marginal gain (loss) that is similar for any initial credibility level. This finding stands in between existing results in the literature: while Schaumburg and Tambalotti (2007) find that most of the gains from commitment are present at low credibility levels, Debortoli et al. (2014) report that substantial gains from increasing credibility are only present at higher degrees of commitment.

This may be due to our model being in between those of Schaumburg and Tambalotti (2007) and Debortoli et al. (2014) in terms of shocks and frictions considered.\(^{14}\) The presence of additional frictions and shocks in the model accentuates the need for central banks to manage expectations more effectively in order to minimise distortions. As the

\(^{12}\)More precisely, we report unconditional welfare losses. These are given by the function \( L_\gamma(\cdot) \) defined in Section 2.4 and represent welfare before knowing the realisation of the current shocks. Alternatively, one can compute conditional welfare losses which are defined by the value of welfare knowing the realisation of the shocks in the current period. In our model, when the economy is initialised at steady state, the values of unconditional and conditional welfare losses are almost identical across several calibration of the probability of commitment, and thus all results are similar. Additional details of these definitions are available in Debortoli et al. (2014).

\(^{13}\)Alternatively, we can measure the welfare difference between a given level of credibility and full discretion in consumption equivalent variation units. This is given by \( CEV(\%) = 100 \left( \frac{L_0 - L_\gamma}{\tilde{C}(\frac{\partial U}{\partial C}|_{s.s.})} \right) \), where \( \tilde{C}(\frac{\partial U}{\partial C}|_{s.s.}) \) implies how much welfare increases if steady state consumption increases by one percent. Using this measure, the total welfare gain from full commitment is 2.2% and the welfare gain from an intermediate level of credibility (\( \gamma = 0.5 \)) is 1.1%.

\(^{14}\)Schaumburg and Tambalotti (2007) evaluate the welfare gains from credibility in a NK model with price rigidity and price cost-push shocks only. Debortoli et al. (2014) consider optimal policy under commitment in a Smets and Wouters (2007) model with nominal and real rigidities as well as additional shocks. Another difference is that the central bank in Debortoli et al. (2014) has preferences without inflation bias—the output gap target is zero—while in Schaumburg and Tambalotti (2007) the central bank has an inflation bias.
Notes: The figure plots the welfare gains associated with a probability of commitment as a fraction of the total gains from commitment. That is, the welfare gains from discretion to an imperfect credibility policy with $\gamma$, $(L_0 - L_{\gamma})$, are normalised by the total gains from commitment $(L_0 - L_1)$. The dashed line is the 45 degrees line.

number of distortions in the model increase, so does the need for relatively higher levels of credibility in order for welfare improvements to be present.

Welfare-based measures give us valuable information on the gains from increased credibility but they hide the relative contribution of output gap and inflation volatilities to the overall loss. Indeed, depending on the relative weights in the loss function, lower welfare losses are achieved by optimising the trade-off between output gap and inflation volatilities. An interesting finding is that the nature of this trade-off changes with the level of commitment.

Given a probability of commitment $\gamma$, standard deviations of welfare-relevant variables are computed and reported in Figure 2. When the credibility of the central bank approaches the limiting case of full commitment, the planner can effectively reduce the variances of output gap, price inflation, and wage inflation. However, starting from lower credibility levels, any improvement in welfare due to higher credibility is achieved by reducing both price and wage inflation volatilities at a cost of a higher output gap volatility. The reason is that stabilising price and wage inflation is relatively more important than stabilising output gap deviations; given the relative weights in the loss
Figure 2: Credibility and target variables volatility.

Notes: The figure reports the standard deviations of output gap, price inflation, and wage inflation with $\gamma \in \{1, 0.9, 0.7, 0.5, 0.3\}$. The left panel shows the volatility of output gap and the volatility of price inflation. The right panel shows the volatility of output gap and the volatility of wage inflation. For each degree of commitment, the weight on the output gap takes values in the interval $[2\psi_y, 0.5\psi_y]$.

function, a reduction in price or wage inflation volatility is more beneficial than the same reduction in output gap volatility.\footnote{As Figure 2 shows, this finding is robust to alternative calibrations of the weight attached to the output gap ($\psi_y$).}

The result that higher credibility leads to higher output-gap volatility was already present in Schaumburg and Tambalotti (2007); in their case the planner achieves lower price inflation at the cost of higher output-gap volatility. In our model, the result is very similar but both price and wage inflation volatilities are lowered. This highlights the nature of the output-inflation stabilisation trade-off under different credibility levels. Even in a model with additional nominal (wage) rigidities, the importance of output gap deviations for welfare remains lower compared to that of price and wage inflation. In response to exogenous shocks, policymakers with higher credibility are better able to keep price and wage inflation low by managing expectations. This is achieved by
allowing larger future deviations of output from its target, a mechanism that is explained in more detail in the next section.

4 Credibility and business cycle properties

In order to better understand the transmission mechanism and properties of optimal policy under loose commitment, this section reports impulse responses and simulated moments of endogenous variables. Due to the nature of the loose commitment policy, the response of endogenous variables at any point in time is dependent on the realisation of a Bernoulli process \( \{ \eta_t \}^\infty_{t=0} \). Whenever a reoptimisation is triggered, \( \eta_t = 0 \), the planner reneges on past promises and reformulates a new plan. According to recursive contracts theory (Marcet and Marimon, 2019), information on past promises is completely summarised by Lagrange multipliers, \( \lambda_t \), which enter the state space as co-state variables. The random variable that controls reoptimisations \( \eta_t \) is added to the decision rules as a multiplicative term to the vector of Lagrange multipliers, so that whenever a reoptimisation occurs the Lagrange multipliers are set to zero, \( \eta_t \lambda_t = 0 \), and past promises become irrelevant.

Since the reoptimisation shock \( \eta_t \) enters non-linearly in the decision rules, this creates non-trivial dynamics of endogenous variables. To better understand how the central bank responds to exogenous shocks and their effects on second moments, two types of impulse responses can be computed. First, one can compute impulse responses subject to a particular realisation of \( \{ \eta_t \}^\infty_{t=0} \). Second, one can compute impulse responses where all possible histories of reoptimisation are integrated to show the average behaviour of endogenous variables.

Figure 3 shows the impulse responses to a wage markup shock under a loose commitment policy with \( \gamma = 0.8 \) as well as the limiting cases of full commitment and discretion. Given the nature of the reoptimisation shocks, the probability of a central banker to remain committed to the announced plan for the next \( k \) quarters follows a geometric distribution with an expected value of \( 1/(1 - \gamma) = 5 \). Therefore, we assume a history of reoptimisations where the planner reneges on past promises and reformulates a new plan every five quarters. To better isolate the effects of reoptimisations, Figure 3 also plots the case where reoptimisations never occur even though credibility is imperfect.

Under the full commitment policy, the planner is able to very effectively stabilise price inflation from the persistent wage shock and to quickly reduce wage inflation by managing expectations of future price and wage inflation. However, this anchoring of price and wage inflation is only achieved by promising a recession and undershooting
Figure 3: Impulse responses to a persistent wage markup shock.

Notes: The figure shows the responses of endogenous variables when $\gamma = 0.8$ subject to a history of reoptimisations where the planner reneges on its past promises every 5 quarters. This is compared to impulse responses under full commitment, discretion, and $\gamma = 0.8$ when reoptimisation never occurs.

wage inflation, which becomes negative after roughly 5 quarters before converging back to target. Clearly, this promise is time-inconsistent.

Under the loose commitment policy, the (partial) lack of credibility implies that the planner is not able to control expectations as effectively as in the full commitment case, which is ultimately reflected in a worse outcome—higher price and wage inflation and a deeper recession. The history with a reoptimisation in the fifth quarter (solid blue line) illustrates the time-inconsistency and the incentives that the planner faces. If the planner is allowed to reoptimise, it abandons the promises of a deep recession and negative inflation.\textsuperscript{16}

Due to the discontinuities created by the random process $\eta_t$, impulse responses conditional on a particular history of reoptimisations are not necessarily representative

\textsuperscript{16}The planner abandons previous promises but still makes new promises regarding the future. Since the shock is persistent, it is optimal for the planner not to fully close the output gap, and still to promise a recession. However, the newly planned recession is milder since the shock has receded.
of the average behaviour of endogenous variables, therefore making it more difficult to compare impulse responses and second moments. For this reason, we also report average impulse response functions, in which all histories are weighted by their probability and integrated to calculate the expected path.

Figure 4 shows the optimal response of a central banker with a degree of commitment $\gamma \in \{1, 0.9, 0.5, 0.3, 0\}$ to a persistent price cost-push shock. Central bankers with high credibility can bring down price inflation at a faster rate than low credibility ones. Nevertheless, the difference in price inflation trajectories is quantitatively small. The usual trade-off between inflation and output gap still applies: better price inflation outcomes come at a cost of a more persistent recession.

Wage inflation comoves negatively with price inflation at high degrees of commitment while it comoves positively at lower degrees. This means that more credible planners manage to promise low wage inflation to counteract price inflation, avoiding the feedback loop between the two variables. But low credibility central bankers do not manage to stop this feedback loop, where higher prices lead to higher nominal wages which in turn lead to higher marginal costs and higher prices.

Figure 5 plots the average impulse response function for wage markup shocks. In the initial period, wage inflation goes up in response to the shock. Central banks with high levels of credibility manage to better contain this initial increase in wage inflation. The reason is that these central banks promise future wage inflation below target, which is time-inconsistent as it implies a cost in the future but allows to contain the initial increase in wage inflation. Since wage and price inflation are connected through the costs and pricing decisions of firms, price inflation is also closer to target when credibility is high.

Figure 6 reports the response of endogenous variables to a technology shock. When both prices and wages are sticky, the efficient allocation cannot be achieved, and thus technology shocks affect the variables and their natural counterparts differently. In this scenario the optimal response is to catch up with the movements in the natural output and natural real wage by minimising the distortion created by price and wage dispersion. Therefore, in response to a technology shock the real wage rises but at considerably slower pace than its natural counterpart. As Figure 6 shows, this is achieved by contemporaneously increasing nominal wages and reducing prices. Central bank credibility does not play a big role here as different degrees of credibility lead to similar responses.

In order to get a better insight into the sources of welfare gains from commitment, Table 2 reports model simulated moments for several degrees of commitment. As high-
Figure 4: Average impulse responses to a persistent price cost-push shock.

Notes: The figure shows the average impulse responses in response to a price cost-push shock and for different degrees of commitment. The average is computed over 10,000 different impulse responses where for each one we draw a random realisation of the reoptimisation process \( \eta_t \) for each commitment level.

Lighted in previous sections, higher credibility is associated with lower price and wage inflation volatilities but higher output gap variance. The standard deviation of real wages is decreasing in the credibility level. Cross correlations with output are affected by credibility as well. Since central bankers with higher credibility are better able to insulate price and wage inflation from shocks, the co-movements of these variables with output are smaller.\(^{17}\)

Finally, loose commitment changes the variance decomposition for some variables, as reported in Table 3. For instance, under full commitment, the variability of price inflation is almost entirely due to price cost-push shocks. However, for low levels of

\(^{17}\)Small cross correlations with output might also result from a composition of positive and negative correlations. In particular, when the model is simulated conditional on price cost-push shocks only, the cross correlation of wage inflation with output becomes positive at higher degrees of commitment. Tables containing empirical moments conditional on shocks are reported in the Appendix A-2.
Figure 5: Average impulse responses to a persistent wage markup shock.

Notes: The figure shows the average impulse responses in response to a wage markup shock and for different degrees of commitment. The average is computed over 10,000 different impulse responses where for each one we draw a random realisation of the reoptimisation process \( \{\eta_t\}_{t=1}^{15} \).
Figure 6: Average impulse responses to a persistent technology shock.

Notes: The figure shows the average impulse responses in response to a technology shock and for different degrees of commitment. The average is computed over 10,000 different impulse responses where for each one we draw a random realisation of the reoptimisation process \( \{ \eta_t \}_{t=1}^{15} \).

credibility, wage markup shocks gain importance. As shown in Figure 5, the reason is that central banks with low credibility do not manage expectations effectively and let wage inflation spill into a feedback loop with price inflation.
Table 2: Simulated moments

<table>
<thead>
<tr>
<th>Variable</th>
<th>0.0</th>
<th>0.3</th>
<th>0.5</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of commitment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output gap $\bar{y}$</td>
<td>2.760</td>
<td>3.514</td>
<td>4.007</td>
<td>4.424</td>
<td>4.313</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>0.603</td>
<td>0.540</td>
<td>0.483</td>
<td>0.352</td>
<td>0.331</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.763</td>
<td>0.668</td>
<td>0.583</td>
<td>0.390</td>
<td>0.351</td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>3.091</td>
<td>2.957</td>
<td>2.843</td>
<td>2.602</td>
<td>2.553</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>1.037</td>
<td>1.402</td>
<td>1.356</td>
<td>0.826</td>
<td>0.709</td>
</tr>
<tr>
<td>Output $y$</td>
<td>3.118</td>
<td>3.803</td>
<td>4.264</td>
<td>4.660</td>
<td>4.555</td>
</tr>
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</table>

Cross correlation with output

<table>
<thead>
<tr>
<th>Variable</th>
<th>0.0</th>
<th>0.3</th>
<th>0.5</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap $\bar{y}$</td>
<td>0.887</td>
<td>0.876</td>
<td>0.770</td>
<td>-0.762</td>
<td>-0.470</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>-0.714</td>
<td>-0.639</td>
<td>-0.668</td>
<td>-0.213</td>
<td>-0.064</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>-0.876</td>
<td>-0.770</td>
<td>-0.468</td>
<td>-0.264</td>
<td>-0.112</td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>-0.368</td>
<td>-0.366</td>
<td>-0.360</td>
<td>-0.348</td>
<td>-0.357</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>-0.911</td>
<td>-0.798</td>
<td>-0.762</td>
<td>-0.470</td>
<td>-0.265</td>
</tr>
</tbody>
</table>

Notes: Standard deviations and cross correlations with output are reported for each degree of commitment $\gamma \in \{1, 0.9, 0.5, 0.3, 0\}$. Moments are computed by simulating the model 5,000 times for 1,000 periods.
Table 3: Variance decomposition

<table>
<thead>
<tr>
<th>Shock</th>
<th>Degree of commitment</th>
<th>1.0</th>
<th>0.9</th>
<th>0.5</th>
<th>0.3</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output gap</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost-push</td>
<td>( u^p )</td>
<td>0.013</td>
<td>0.015</td>
<td>0.013</td>
<td>0.012</td>
<td>0.011</td>
</tr>
<tr>
<td>Wage</td>
<td>( u^w )</td>
<td>0.987</td>
<td>0.985</td>
<td>0.987</td>
<td>0.988</td>
<td>0.989</td>
</tr>
<tr>
<td>Technology</td>
<td>( a )</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
<td>0*</td>
</tr>
<tr>
<td>Demand</td>
<td>( z )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Price inflation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost-push</td>
<td>( u^p )</td>
<td>0.95</td>
<td>0.86</td>
<td>0.504</td>
<td>0.416</td>
<td>0.344</td>
</tr>
<tr>
<td>Wage</td>
<td>( u^w )</td>
<td>0*</td>
<td>0.095</td>
<td>0.471</td>
<td>0.564</td>
<td>0.639</td>
</tr>
<tr>
<td>Technology</td>
<td>( a )</td>
<td>0.05</td>
<td>0.045</td>
<td>0.025</td>
<td>0.02</td>
<td>0.017</td>
</tr>
<tr>
<td>Demand</td>
<td>( z )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Wage inflation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost-push</td>
<td>( u^p )</td>
<td>0.014</td>
<td>0.012</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
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<tr>
<td>Wage</td>
<td>( u^w )</td>
<td>0.984</td>
<td>0.986</td>
<td>0.993</td>
<td>0.994</td>
<td>0.994</td>
</tr>
<tr>
<td>Technology</td>
<td>( a )</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0*</td>
<td>0*</td>
</tr>
<tr>
<td>Demand</td>
<td>( z )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Interest rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost-push</td>
<td>( u^p )</td>
<td>0.044</td>
<td>0.035</td>
<td>0.037</td>
<td>0.043</td>
<td>0.085</td>
</tr>
<tr>
<td>Wage</td>
<td>( u^w )</td>
<td>0.865</td>
<td>0.897</td>
<td>0.937</td>
<td>0.932</td>
<td>0.868</td>
</tr>
<tr>
<td>Technology</td>
<td>( a )</td>
<td>0.061</td>
<td>0.046</td>
<td>0.019</td>
<td>0.018</td>
<td>0.033</td>
</tr>
<tr>
<td>Demand</td>
<td>( z )</td>
<td>0.03</td>
<td>0.022</td>
<td>0.008</td>
<td>0.008</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Notes: For each degree of commitment \( \gamma \in \{1, 0.9, 0.5, 0.3, 0.0\} \), the table reports the variance decomposition. Values smaller than 0.001 are reported as 0\*.
5 Wage flexibility and welfare

The model features two key frictions, price and wage stickiness. While reducing one of those distortions would bring the model closer to a frictionless economy, the theory of second best shows that doing so is not necessarily welfare improving. Galí (2013) and Galí and Monacelli (2016) report cases where increasing wage flexibility may lead to welfare losses.\footnote{See also Billi and Galí (2020) for a discussion of wage flexibility in the zero lower bound context and Bhattarai et al. (2018) for a discussion of price flexibility.} We contribute to the existent literature on two fronts: i) by examining the effects of intermediate levels of credibility, ii) by examining the effects of price cost-push and wage markup shocks.\footnote{For instance, Galí (2013) examines a model very similar to ours but with neither price cost-push shocks nor wage markup shocks.} As we will show later, these two aspects are key.

5.1 Technology shocks

Figure 7 plots the average period welfare loss due to technology shocks as a function of wage rigidity. Welfare losses are reported for different levels of credibility, ranging from full discretion ($\gamma = 0$) to high credibility ($\gamma = 0.9$). Total welfare losses are decomposed into the contribution of price inflation volatility, wage inflation volatility, and output gap volatility according to equation (9).\footnote{More precisely, and as in Galí (2013), we use the equivalent welfare formulation with variances, i.e.: $L = \frac{1}{2} \left[ \psi_y \text{var}(\tilde{y}_t) + \psi_p \text{var}(\pi^*_t) + \psi_w \text{var}(\pi^*_t) \right]$ as $\beta \to 1$.} Figure 7 reports welfare losses for two alternative calibrations of the price rigidity parameter: a baseline calibration ($\theta_p = 0.75$, left column) and a case of high price rigidity ($\theta_p = 0.95$, right column).

Welfare losses due to wage inflation volatility (solid line with circles) are non-monotone in wage flexibility. This result is intuitive. If wages were completely flexible, then the weight on wage inflation in the central bank’s loss function ($\psi_w$) is zero. If wages were completely sticky, then the volatility of wage inflation is zero. Therefore, as we move between fully rigid and fully flexible wages, welfare losses due to wage inflation volatility must be non-monotone.

We observe that the output gap is largely stabilised in response to technology shocks. This result is known and follows from the fact that while the divine coincidence does not exactly hold in this model, it does so approximately. In a model with either flexible wages or flexible prices, the output gap would not move with respect to technology shocks. In models with both sticky wages and sticky prices, this is no longer the case but the effects are small.\footnote{See Galí (2015) for a textbook exposition on this issue and also Debortoli et al. (2019) and Justini-ano et al. (2013).}
Figure 7: Welfare loss to technology shocks.

Notes: The figure displays the decomposition of the average period welfare loss conditional on technology shocks into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity. Left column shows the welfare loss under baseline price rigidity ($\theta_p = 0.75$) with: full discretion ($\gamma = 0$, Panel A), $\gamma = 0.5$ (Panel C), and $\gamma = 0.9$ (Panel E). Right column shows the welfare loss under high price rigidity ($\theta_p = 0.95$) with: full discretion ($\gamma = 0$, Panel B), $\gamma = 0.5$ (Panel D), and $\gamma = 0.9$ (Panel F). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
We can also observe that with more wage flexibility, the costs associated with price inflation are smaller. The main reason is that when wages are more flexible, the weight on wage inflation is smaller and thus the central bank focuses more strongly on stabilising price inflation. Also in response to technology shocks, the real wage needs to adjust to productivity; if wages are more flexible, the adjustment in prices can be smaller.\textsuperscript{22}

Overall, whether wage flexibility is welfare improving, depends on the cost of price inflation stabilisation. As Figure 7 (right column) shows, when the degree of price rigidity is very high, total welfare losses can increase with wage flexibility if wages are sufficiently sticky. Given the high degree of price rigidity, the central bank focuses almost exclusively on stabilising price inflation. As a result, more flexible wages can increase wage inflation volatility making price inflation stabilisation more costly in terms of higher wage inflation and output gap volatility.

The effectiveness of monetary policy matters as well. If policy is not optimal, e.g. follows a Taylor rule, or is constrained, wage and price inflation can comove and increased wage flexibility can lead to higher inflation volatility in a feedback loop. This happens in our model in response to other shocks.\textsuperscript{23}

In the case of technology shocks and when prices are very rigid, imperfect credibility enlarges the parameter region where wage flexibility may be welfare detrimental. As Figure 7 (right column) shows, lower levels of commitment are associated with larger welfare losses due to wage inflation volatility. As a result, a less credible monetary policy increases the range of initial wage rigidity values over which more flexible wages lead to higher total welfare losses.

Most of the analysis in the literature regarding the welfare losses of wage flexibility focus on technology and demand shocks.\textsuperscript{24} However, the empirical literature shows that price cost-push shocks and, especially, wage markup shocks are an important component of business cycles (e.g. Smets and Wouters, 2007) and welfare (e.g. Debortoli et al., 2019). This is especially true since a central bank behaving optimally can counteract demand shocks, and technology shocks only introduce a mild trade-off in a sticky price

\textsuperscript{22}Similarly to the non-monotonicity of the wage inflation component, this result is consistent across several calibrations of the price rigidity parameter. For more details refer to Figure A-2 in Appendix A-3.

\textsuperscript{23}Even with respect to technology shocks, notice that price and wage inflation comove after some periods, and hence wage flexibility can lead to higher wage volatility and then higher price inflation volatility.

\textsuperscript{24}Demand shocks only produce welfare losses with a sub-optimal policy such as an interest rate rule. In that case, the intuition for hump-shaped losses with respect to wage flexibility is straightforward. The efficient allocation with flexible prices and flexible wages features a constant real wage. This allocation is also achieved with completely sticky prices and completely sticky wages, it follows that for intermediate degrees of stickiness welfare must be non-monotone.
and sticky wage model (see discussion above and Table 3).

### 5.2 Price cost-push shocks

Figure 8 plots the average period welfare loss due to price cost-push shocks as a function of wage rigidity for different levels of credibility. Welfare losses are reported for both a baseline (Figure 8, left column) and a high degree of price rigidity (right column). When credibility is high ($\gamma = 0.9$), if wages are more flexible, the volatility of wage inflation increases but that of price inflation decreases. The reason is that wages can do a larger part of the adjustment and therefore mitigate the need to adjust prices. In such case, more wage flexibility reduces losses of inflation volatility as well as total losses.

The welfare gains from wage flexibility, however, are conditional on the policymaker having a high enough degree of commitment. As mentioned earlier, monetary policy is key in avoiding a feedback loop between higher price inflation and wage inflation volatility. When credibility is low, inflation losses may increase because higher wage flexibility implies higher price inflation volatility. This will happen if monetary policy does not counteract the impact of extra wage volatility on prices. If a central bank has high credibility, then it uses expectations management to contain inflation volatility and inflation losses go down as the central bank can focus on price inflation. However, if credibility is low, then higher wage flexibility leads to higher wage and price inflation in a feedback loop.

These effects and their dependence on the level of credibility can be observed in the average impulse response function shown in Figure 4. Under full commitment, the central bank can keep the rise in price inflation to be moderate. This is achieved by managing expectations and promising future low price inflation and negative wage inflation. In contrast, with a low level of commitment, given the inability of managing expectations, the central bank experiences higher price inflation combined with positive wage inflation, leading to a feedback loop between more volatile wage inflation, which in turn leads to more volatile price inflation. In these low credibility cases, stickier wages help the central bank to stabilise the economy.\(^{25}\)

Figure 8 (right column) also reports the case of very sticky prices. Similarly to technology shocks, a high degree of price rigidity along with lower levels of credibility increases the range of initial wage rigidity values over which more flexible wages reduce

\(^{25}\)The correlation between price and wage inflation conditional on a price cost-push shock is negative under full commitment. However, price inflation and wage inflation become positively correlated when the credibility level becomes lower.
Figure 8: Welfare loss to price cost-push shocks.

Notes: The figure displays the decomposition of the average period welfare loss conditional on price cost-push shocks into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity. Left column shows the welfare loss under baseline price rigidity ($\theta_p = 0.75$) with: full discretion ($\gamma = 0$, Panel A), $\gamma = 0.5$ (Panel C), and $\gamma = 0.9$ (Panel E). Right column shows the welfare loss under high price rigidity ($\theta_p = 0.95$) with: full discretion ($\gamma = 0$, Panel B), $\gamma = 0.5$ (Panel D), and $\gamma = 0.9$ (Panel F). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
**Figure 9:** Welfare loss to wage markup shocks.

A. $\theta_p = 0.75, \gamma = 0$

B. $\theta_p = 0.95, \gamma = 0$

C. $\theta_p = 0.75, \gamma = 0.5$

D. $\theta_p = 0.95, \gamma = 0.5$

E. $\theta_p = 0.75, \gamma = 0.9$

F. $\theta_p = 0.95, \gamma = 0.9$

**Notes:** The figure displays the decomposition of the average period welfare loss conditional on wage markup shocks into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity. Left column shows the welfare loss under baseline price rigidity ($\theta_p = 0.75$) with: full discretion ($\gamma = 0$, Panel A), $\gamma = 0.5$ (Panel C), and $\gamma = 0.9$ (Panel E). Right column shows the welfare loss under high price rigidity ($\theta_p = 0.95$) with: full discretion ($\gamma = 0$, Panel B), $\gamma = 0.5$ (Panel D), and $\gamma = 0.9$ (Panel F). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
welfare. As the relative weight on wage volatility in the loss function is lower due to high price rigidity, more flexible wages can lead to even higher wage inflation. If monetary policy is constrained due to a lower level of credibility, the ability to manage expectations is reduced and higher wage inflation volatility may lead to higher price inflation volatility and price inflation losses.26

5.3 Wage markup shocks

Figure 9 plots the average period welfare loss due to wage markup shocks. In this case, wage flexibility is welfare improving at all levels of credibility. This result is intuitive because the wage markup shock creates a direct distortion in wage levels. When the wage markup shock hits, nominal wage inflation increases and so do real wages. If wages are more flexible, this distortion can be corrected more rapidly. In addition, welfare losses of wage dispersion become less important to households, which is reflected in a lower value of the weight on wage inflation ($\psi_w$) in the welfare loss function. As Figure 9 (right column) shows, this also holds true for extreme calibrations of the price rigidity parameter. If prices are very rigid, most of the adjustment in real wages is brought by movements in nominal wages, and thus more flexible wages allows the policy maker to close the real wage gap more quickly.

Another important consideration is that, due to the reasons just explained, more flexible wages are translated into a less volatile wage inflation when wage markup shocks are considered (unlike in response to technology shocks). In addition, higher wage flexibility also leads to lower price inflation volatility because wages are interconnected with prices through the pricing decisions of firms and the labour market. As such, wage flexibility also makes it easier for central banks to stabilise price inflation and the output gap. This is true for central banks with lower levels of credibility as well, which makes wage flexibility welfare improving regardless of the central bank’s credibility.27

5.4 All shocks

The previous subsections showed that wage flexibility can increase welfare losses in response to technology and price cost-push shocks. This result is more likely if prices

26 Notice that due to a very high degree of price rigidity, total welfare losses are almost entirely driven by inflation losses. As Figure 8 Panel B (top row, right column) shows, this is especially true in the case of high price rigidity and full discretion.

27 Imperfect credibility, however, changes the relative composition of total welfare losses, with output gap losses playing a larger role at higher degrees of commitment. This can be seen in Figure 9 and it is discussed in more detail in Section 3.
Figure 10: Welfare loss to all shocks.

Notes: The figure displays the decomposition of the average period welfare loss in response to all shocks into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity. Left column shows the welfare loss under baseline price rigidity ($\theta_p = 0.75$) with: full discretion ($\gamma = 0$, Panel A), $\gamma = 0.5$ (Panel C), and $\gamma = 0.9$ (Panel E). Right column shows the welfare loss under high price rigidity ($\theta_p = 0.95$) with: full discretion ($\gamma = 0$, Panel B), $\gamma = 0.5$ (Panel D), and $\gamma = 0.9$ (Panel F). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
are very rigid and the policymaker has a lower credibility. In contrast, wage flexibility is welfare improving in response to wage markup shocks. Figure 10 plots the average period welfare loss when all shocks are active for different levels of credibility. Welfare losses are reported for both a baseline (Figure 10, left column) and a high degree of price rigidity (right column). For both calibrations, wage flexibility is welfare improving.

These results are driven by the relative contribution of each type of shock to welfare losses (see Table 3). Because we base our calibration on the seminal empirical work of Smets and Wouters (2007), wage markup shocks are a relevant force driving business cycles and, therefore, of our analysis. As we had discussed previously, intermediate degrees of credibility increase the range of cases where wage flexibility leads to welfare losses. But such reasoning—that less credible monetary policy is unable to prevent a feedback loop between wage and price inflation—was based on price cost-push shocks. Once all types of shocks are incorporated, and given the role of wage markup shocks, wage flexibility is welfare improving even if credibility is low.

Because there is some uncertainty about the role of markup shocks over the business cycle, we also consider a case where only a small proportion of the observed variation in inflation and wages is driven by these shocks. We use an alternative calibration where we set the standard deviation of wage markup shocks to a third of their baseline value and to zero that of cost-push shocks. For the wage markup shock, this calibration can be motivated by the work of Galí et al. (2012), who distinguish between labour supply and wage markup shocks by including the unemployment rate as an observable when estimating a model similar to the Smets and Wouters (2007) model. For the price markup shock, our choice follows Justiniano et al. (2013) who assume that almost 90% of the markup shock variances stem from variations in the inflation target. In this case, the results remain similar to the baseline.

6 Conclusions

This paper considers optimal monetary policy in a framework that spans the polar cases of full commitment and full discretion. Under loose commitment, the monetary authority commits to a state-contingent optimal policy plan but, with a given probability, occasionally reneges on past promises and announces a new plan. This probability

\footnote{Figures A-6 and A-7 in Appendix A-3 show the case with all shocks except wage markup shocks, confirming these results. If wage markup shocks are not present, wage flexibility is not necessarily welfare improving especially if credibility is not too high.}

\footnote{Figures A-9 and A-10 in Appendix A-3 show that the qualitative results are very similar to the baseline case.}
is known to all economic agents, which incorporate it in their information set when forming expectations and making decisions. The degree of commitment can therefore be interpreted as central bank credibility.

We apply this optimal monetary policy setting to a standard New Keynesian model with price and wage rigidities. This canonical model has the key advantage that analytical and microfounded expressions for welfare can be used, which provides a more transparent and rigorous framework for optimal policy evaluation. In addition, this model retains key frictions for evaluating the trade-offs of optimal monetary policy.

The welfare gain from increasing credibility is approximately independent of the initial credibility level, i.e. the marginal reduction in welfare losses is nearly equal for low, medium, or high degrees of commitment. The trade-off between stabilising output gap and inflation changes with the probability of commitment. Higher credibility translates into lower volatilities of price and wage inflation but not necessarily lower output-gap volatility. This means that the volatility of output is not a good gauge of credibility. The paper characterises the response of endogenous variables to exogenous shocks and how these change with the degree of commitment and occurrence of reoptimisations. The variance decomposition shows that the wage markup shock is the main driver of economic fluctuations and that these shocks are better contained, even in relative terms, when credibility is high.

The paper then examines the debate of whether wage flexibility is welfare improving. We bring two important elements to the analysis: imperfect credibility and wage markup shocks. We show that the degree of credibility can indeed be important. If monetary policy is not effective, less potent monetary policy may not counteract the inflationary effects of more flexible wages. This occurs when the source of shocks renders a potential feedback loop between wage and price inflation. While imperfect credibility makes wage flexibility more likely to be welfare detrimental, the presence of wage markup shocks are a force in the opposite direction. Wage flexibility is important to dampen the welfare losses of wage markup shocks, and these shocks are a non-negligible source of business cycles. Overall, our results suggest that the welfare effects of wage flexibility may be country-specific. Countries featuring prevalent wage markup shocks would benefit from higher wage flexibility. Countries where the monetary authority is not very credible may find that wage flexibility is less desirable.
References


Online Appendix

A-1 Welfare gains from commitment: an alternative measure

An alternative measure of the gains from commitment is given by the permanent deviation in one of the targets that would equate the welfare loss under the full commitment policy to the loss under imperfect credibility. In other words, this alternative measure is the permanent deviation in either output gap, price inflation, or wage inflation that would leave a planner indifferent between full commitment and a credibility level $\gamma$.

Considering the output gap as the target variable, this measure is formally defined by the permanent deviation in output gap $m_y$ such that

$$
E\sum_{t=0}^{\infty} \beta^t \left\{ \psi_y (\tilde{y}_{t,1} - m_y)^2 + \psi_p (\pi_{t,1}^p)^2 + \psi_w (\pi_{t,1}^w)^2 \right\} = E\sum_{t=0}^{\infty} \beta^t \left\{ \psi_y (\tilde{y}_{t,\gamma})^2 + \psi_p (\pi_{t,\gamma}^p)^2 + \psi_w (\pi_{t,\gamma}^w)^2 \right\}, \tag{A-1}
$$

where $\{\tilde{y}_{t,\gamma}\}_{t=0}^{\infty}$, $\{\pi_{t,\gamma}^p\}_{t=0}^{\infty}$, and $\{\pi_{t,\gamma}^w\}_{t=0}^{\infty}$ denote the optimal paths of output gap, price inflation, and wage inflation under a degree of commitment $\gamma$. Welfare measures based on price and wage inflation, $m_p$ and $m_w$, are defined analogously.

Equation (A-1) can be simplified to obtain $m_y$ as

$$
m_y = \sqrt{\frac{1 - \beta}{\psi_y} (L_\gamma - L_1)}.
$$

Figure A-1 illustrates how these measures—$m_y$, $m_p$, and $m_w$—change with the degree of commitment. As expected, the discretionary policy bears the largest costs with a permanent deviation of price and wage inflation of roughly 4% and 2.75% in annualised terms.
Figure A-1: Alternative welfare measure.

Notes: Each panel reports the permanent deviation in the target variable necessary to match the welfare loss under full commitment to that under imperfect credibility. Values closer to zero are associated with lower welfare losses. Price and wage inflation are in % values.
A-2 Empirical moments

This section reports additional tables with the empirical moments. Each table corresponds to empirical moments of the model conditional on each shock.

Table A-1: Simulated moments conditional on a price cost-push shock.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degree of commitment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td></td>
</tr>
<tr>
<td>Output gap $\tilde{y}$</td>
<td>0.501</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>0.323</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.041</td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>2.007</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>0.148</td>
</tr>
<tr>
<td>Output $y$</td>
<td>0.501</td>
</tr>
<tr>
<td><strong>Cross correlation with output</strong></td>
<td></td>
</tr>
<tr>
<td>Output gap $\tilde{y}$</td>
<td>1</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>-0.192</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.587</td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>0.969</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Notes: Standard deviations and cross correlations with output are reported for each degree of commitment $\gamma \in \{1, 0.9, 0.5, 0.3, 0.0\}$. Moments are computed by simulating the model 5,000 times for 1,000 periods. The standard deviations of the shocks are set to zero except that of price cost-push shocks.
Table A-2: Simulated moments conditional on a wage markup shock.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degree of commitment</th>
<th>1.0</th>
<th>0.9</th>
<th>0.5</th>
<th>0.3</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap $\bar{y}$</td>
<td>Standard deviation</td>
<td>4.284</td>
<td>4.392</td>
<td>3.98</td>
<td>3.492</td>
<td>2.745</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>0.003</td>
<td>0.108</td>
<td>0.331</td>
<td>0.406</td>
<td>0.482</td>
<td></td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.348</td>
<td>0.387</td>
<td>0.581</td>
<td>0.666</td>
<td>0.761</td>
<td></td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>1.399</td>
<td>1.523</td>
<td>1.992</td>
<td>2.173</td>
<td>2.371</td>
<td></td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>0.659</td>
<td>0.782</td>
<td>1.312</td>
<td>1.354</td>
<td>0.966</td>
<td></td>
</tr>
<tr>
<td>Output $y$</td>
<td>4.284</td>
<td>4.392</td>
<td>3.980</td>
<td>3.492</td>
<td>2.745</td>
<td></td>
</tr>
</tbody>
</table>

Cross correlation with output

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cross correlation with output</th>
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<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap $\bar{y}$</td>
<td>Standard deviation</td>
<td>-0.017</td>
<td>-0.473</td>
<td>-0.748</td>
<td>-0.801</td>
<td>-0.885</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>-0.141</td>
<td>-0.296</td>
<td>-0.72</td>
<td>-0.840</td>
<td>-0.997</td>
<td></td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>-1</td>
<td>-0.894</td>
<td>-0.727</td>
<td>-0.709</td>
<td>-0.722</td>
<td></td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>-0.214</td>
<td>-0.444</td>
<td>-0.774</td>
<td>-0.823</td>
<td>-0.981</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Standard deviations and cross correlations with output are reported for each degree of commitment $\gamma \in \{1, 0.9, 0.5, 0.3, 0.0\}$. Moments are computed by simulating the model 5,000 times for 1,000 periods. The standard deviations of the shocks are set to zero except that of wage markup shocks.
Table A-3: Simulated moments conditional on a technology shock.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Degree of commitment</th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.0</td>
<td>0.9</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Output gap $\bar{y}$</td>
<td>0.028</td>
<td>0.036</td>
<td>0.030</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>0.074</td>
<td>0.074</td>
<td>0.077</td>
<td>0.077</td>
<td>0.078</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.019</td>
<td>0.018</td>
<td>0.015</td>
<td>0.014</td>
<td>0.013</td>
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<tr>
<td>Real wage $\omega$</td>
<td>0.725</td>
<td>0.722</td>
<td>0.712</td>
<td>0.711</td>
<td>0.709</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>0.175</td>
<td>0.178</td>
<td>0.185</td>
<td>0.187</td>
<td>0.188</td>
</tr>
<tr>
<td>Output $y$</td>
<td>1.460</td>
<td>1.463</td>
<td>1.456</td>
<td>1.452</td>
<td>1.447</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cross correlation with output</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Output gap $\bar{y}$</td>
<td>0.695</td>
<td>0.620</td>
<td>0.520</td>
<td>0.501</td>
<td>0.476</td>
</tr>
<tr>
<td>Price inflation $\pi^p$</td>
<td>-0.605</td>
<td>-0.638</td>
<td>-0.674</td>
<td>-0.676</td>
<td>-0.674</td>
</tr>
<tr>
<td>Wage inflation $\pi^w$</td>
<td>0.713</td>
<td>0.596</td>
<td>0.444</td>
<td>0.430</td>
<td>0.434</td>
</tr>
<tr>
<td>Real wage $\omega$</td>
<td>0.814</td>
<td>0.813</td>
<td>0.807</td>
<td>0.806</td>
<td>0.806</td>
</tr>
<tr>
<td>Interest rate $i$</td>
<td>-0.961</td>
<td>-0.968</td>
<td>-0.969</td>
<td>-0.967</td>
<td>-0.965</td>
</tr>
</tbody>
</table>

Notes: Standard deviations and cross correlations with output are reported for each degree of commitment $\gamma \in \{1, 0.9, 0.5, 0.3, 0\}$. Moments are computed by simulating the model 5,000 times and 1,000 periods. The standard deviations of the shocks are set to zero except that of technology shocks.
A-3 Welfare and nominal rigidities

This section provides additional insight into the relationship between welfare losses and nominal rigidities. Figure A-2 shows the relative contribution of price inflation, wage inflation, and output gap to total welfare losses under full commitment conditional on technology shocks. Figure A-3 shows welfare losses conditional on technology shocks as a function of the degree of price stickiness ($\theta_p$). The reason for the hump-shaped pattern of welfare in terms of price flexibility is intuitive. Greater price flexibility leads to more price volatility but to a lower weight in the objective function ($\psi_p$). With complete price flexibility the weight would be zero, and with complete price stickiness the volatility would be zero.\footnote{See Bhattarai et al. (2018) for an interesting analysis on the welfare effects of price stickiness.}

Figure A-4 reports welfare losses under full commitment for different calibrations of the price rigidity parameter conditional on price cost-push shocks. Figure A-5 reports welfare losses under full commitment for different calibrations of the price rigidity parameter when all shocks are active.
Figure A-2: Welfare loss to technology shocks: decomposed.

Notes: The figure displays the decomposition of the average period welfare loss into three components as a function of both the degree of price and wage rigidity conditional on technology shocks under full commitment. Each panel reports price inflation, wage inflation, and output gap components of average period welfare loss, respectively. All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
Figure A-3: Welfare loss to technology shocks as a function of price stickiness.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of price rigidity conditional on technology shocks under full commitment. All parameters except price rigidity ($\theta_p$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
**Figure A-4:** Welfare loss to a price cost-push shock: different price stickiness under full commitment.

*Notes:* The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity conditional on price cost-push shocks under full commitment for different degrees of price rigidity. The upper left panel reports the welfare loss with very flexible prices ($\theta_p = 0.05$), the upper right panel reports that with the baseline price rigidity ($\theta_p = 0.75$), and the lower left panel reports that with very sticky prices ($\theta_p = 0.95$). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
Figure A-5: Welfare loss to all shocks: different price stickiness under full commitment.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks under full commitment for different degrees of price rigidity. The upper left panel reports the welfare loss with very flexible prices ($\theta_p = 0.05$), the upper right panel reports that with the baseline price rigidity ($\theta_p = 0.75$), and the lower left panel reports that with very sticky prices ($\theta_p = 0.95$). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
A-3.1 Welfare and wage flexibility without a wage markup shock

Figures A-6, A-7, and A-8 show welfare losses as a function of wage flexibility in a model without wage markup shocks. Figures A-6 and A-7 consider different levels of credibility for the case of baseline and high degree of price rigidity, respectively. Figure A-8 conditions on different degrees of price stickiness ($\theta_p$) and shows welfare losses under full commitment. As discussed in the main text, the presence of wage markup shocks makes welfare increase in the degree of wage flexibility. If we remove this shock from the model, this result can be reversed if credibility is not too high.
Figure A-6: Welfare loss to all shocks except a wage markup shock: baseline price rigidity.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks except wage markup shocks for different levels of credibility. The upper left panel reports the welfare loss under full discretion ($\gamma = 0$), the upper right panel reports that with $\gamma = 0.5$, and the lower left panel reports that with $\gamma = 0.9$. All parameters except wage rigidity ($\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
Figure A-7: Welfare loss to all shocks except a wage markup shock: high price rigidity.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks except wage markup shocks under high price rigidity ($\theta_p = 0.95$) for different levels of credibility. The upper left panel reports the welfare loss under full discretion ($\gamma = 0$), the upper right panel reports that with $\gamma = 0.5$, and the lower left panel reports that with $\gamma = 0.9$. All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
**Figure A-8:** Welfare loss to all shocks except a wage markup shock: different price rigidities under full commitment.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks except wage markup shocks under full commitment for different degrees of price rigidity. The upper left panel reports the welfare loss with very flexible prices ($\theta_p = 0.05$), the upper right panel reports that with the baseline price rigidity ($\theta_p = 0.75$), and the lower left panel reports that with very sticky prices ($\theta_p = 0.95$). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
A-3.2 Welfare and wage flexibility with a small wage markup shock and absent price cost-push shock

Figures A-9 and A-10 report welfare losses as a function of wage rigidity in a model without price cost-push shocks and where the standard deviation of wage markup shocks is set to a third of its baseline value. For the wage markup shock, this calibration can be motivated by the work of Galí et al. (2012), who distinguish between labour supply and wage markup shocks by including the unemployment rate as an observable when estimating a model similar to the Smets and Wouters (2007) model. For the price markup shock, our choice follows Justiniano et al. (2013) who assume that almost 90% of the markup shock variances stem from variations in the inflation target. In this case, the qualitative results remain similar to the baseline. Figure A-9 shows welfare losses under different levels of credibility for both a baseline ($\theta_p = 0.75$, left column) and a high degree of price rigidity ($\theta_p = 0.95$, right column). Figure A-10 shows welfare losses under full commitment for different calibrations of the price rigidity parameter.
Figure A-9: Welfare loss to all shocks except price cost-push shock and with a smaller standard deviation of the wage markup shock.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks without price cost-push shock and one third of baseline wage markup shock standard deviation for different levels of credibility. Left column shows the welfare loss under baseline price rigidity ($\theta_p = 0.75$) with: full discretion ($\gamma = 0$, Panel A), $\gamma = 0.5$ (Panel C), and $\gamma = 0.9$ (Panel E). Right column shows the welfare loss under high price rigidity ($\theta_p = 0.95$) with: full discretion ($\gamma = 0$, Panel B), $\gamma = 0.5$ (Panel D), and $\gamma = 0.9$ (Panel F). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.
Figure A-10: Welfare loss to all shocks except price cost-push shock and with a smaller standard deviation of the wage markup shock: different price rigidities under full commitment.

Notes: The figure displays the decomposition of the average period welfare loss into three components, price inflation, wage inflation, and output gap, as a function of the degree of wage rigidity in response to all shocks without price cost-push shock and one third of baseline wage markup shock standard deviation under full commitment for different degrees of price rigidity. The upper left panel reports the welfare loss with very flexible prices ($\theta_p = 0.05$), the upper right panel reports that with the baseline price rigidity ($\theta_p = 0.75$), and the lower left panel reports that with very sticky prices ($\theta_p = 0.95$). All parameters except price and wage rigidities ($\theta_p$ and $\theta_w$) are set at their baseline values. The welfare losses are reported as a fraction of steady-state consumption level.