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Abstract

We add downward nominal wage rigidity to a standard New Keynesian model with sticky prices and wages, where the zero lower bound on nominal interest rates is allowed to bind. We find that wage rigidity not only reduces the frequency of zero bound episodes but also mitigates the severity of corresponding recessions. As a result, previous studies abstracting from the presence of wage rigidity may have overemphasized the need for increasing the inflation target to offset the costs associated with hitting the zero bound. Moreover, our findings add to the recent debate on the presumed benefits of wage flexibility that has arisen in the aftermath of the Great Recession.

Bank topics: Monetary policy framework; Inflation targets; Labour markets
JEL codes: E24, E32, E52

Résumé

Nous intégrons la rigidité à la baisse des salaires nominaux à un modèle de type nouveau Keynésien standard à prix et salaires rigides dans lequel la borne du zéro des taux d'intérêt constitue parfois une contrainte. Nous constatons que la rigidité des salaires non seulement réduit la fréquence des épisodes où les taux d'intérêt nominaux atteignent la borne du zéro, mais atténue la gravité des récessions concomitantes. Il en découle que les études antérieures qui ne prenaient pas en compte la rigidité des salaires pourraient avoir accordé trop d'importance au relèvement de la cible d'inflation comme moyen de contrebalancer les coûts associés à l'atteinte de cette borne. De plus, nos constats contribuent à faire avancer le débat récent, lancé dans la foulée de la Grande Récession, sur les avantages présumés de la flexibilité des salaires.

Sujets : Cadre de la politique monétaire ; Cibles d'inflation ; Marchés du travail
Codes JEL : E24 ; E32 ; E52

Non-technical summary

Many studies have investigated the macroeconomic implications of downward nominal wage rigidity (DNWR) and the zero lower bound on nominal interest rates (ZLB). While much of the existing literature has analyzed the two issues separately, our paper focuses on their interaction. In particular, we assess whether and how the presence of DNWR may affect the cost of ZLB episodes.

We start with a standard New Keynesian model with sticky prices and wages. Monetary policy is represented by an estimated interest rate rule that targets inflation and output fluctuations, as well as the lagged nominal interest rate. Conditional on this rule and a set of demand and supply shocks, the model is simulated over a range of inflation targets between zero and five. We then consider three variations of the baseline model: a version in which the ZLB is explicitly taken into account; a version that includes DNWR, modeled by placing a lower bound on the growth of nominal wages, but not the ZLB; and a final version that incorporates DNWR and the ZLB simultaneously.

We find that combining DNWR with the ZLB reduces both the frequency and duration of ZLB spells but, most importantly, DNWR reduces the welfare cost of these spells. DNWR acts through an extensive margin that moderates the frequency of ZLB episodes for any given level of the inflation target. In particular, DNWR attenuates the impact of demand shocks on the real marginal cost and, thus, on inflation and the nominal interest rate. As a result, when DNWR is introduced, larger shocks are required for the nominal interest rate to hit its lower bound relative to the model with only the zero bound. Furthermore, we find that DNWR affects the cost of episodes at the ZLB through an intensive margin: when a ZLB occurrence materializes, the corresponding recession is found to be milder and the associated welfare costs to be lower compared with a flexible-wage economy. Wage rigidity establishes a floor for actual and expected inflation, allowing the real interest rate to fall further than in a flexible-wage economy. Therefore, DNWR acts as a substitute for a lower policy interest rate when the economy experiences a spell at the ZLB.

In addition to the main results, our findings can also be viewed as overturning the conventional wisdom on the benefits of raising an inflation target as well as of greater nominal wage flexibility. Increasing either the inflation target or the flexibility of nominal wages would reduce the traction of DNWR and, therefore, the aforementioned stimulus to aggregate demand when interest rates hit their zero bound.

1. Introduction

Downward nominal wage rigidity (DNWR) and the zero lower bound on nominal interest rates (ZLB) are frequently identified as key factors motivating the need for positive inflation targets. Ball (2014), for example, argues that the ZLB alone warrants an inflation target of four percent, well outside the range that most central banks currently target. Benigno and Ricci (2011) study the macroeconomic implications of DNWR without consideration of the ZLB using a dynamic stochastic general equilibrium model. They find substantial economic costs at low inflation and that a moderate rate of inflation may help reduce economic costs by greasing relative wage adjustments. Although the impact of these two issues has been studied extensively in isolation, little attention has been given to their effects when both frictions are considered in concert. This paper takes a first step towards filling this gap by introducing DNWR into an otherwise standard New Keynesian (NK) model with sticky prices and wages, along with the ZLB. We then use the model to explore the way that DNWR modulates the costs associated with the ZLB. As forcefully argued by Williams (2016), a better understanding of these issues is needed to gauge the resilience of inflation targeting in a world of low interest rates.

Before previewing the findings, it is useful to review briefly the conventional wisdom on DNWR and ZLB in two parts. The first involves an extensive margin, since DNWR suppresses deflation and thus puts upward pressure on nominal rates, making ZLB episodes less likely (Coibion et al. (2012)). The second part is a countervailing intensive margin; DNWR is thought to exacerbate ZLB episodes once underway since firms are forced to reduce labor costs through lay-offs rather than wage adjustments. Although the extensive margin highlighted by Coibion et al. (2012) still operates in our framework, the conventional wisdom corresponding to the intensive margin is overturned. Broadly speaking, this occurs because the conventional wisdom was likely developed in the context of simple models that treated DNWR as the only source of nominal friction in the economy. In particular, we find that for even moderate degrees of goods price stickiness (such as two quarters), DNWR mitigates the costs of the ZLB. As Galí (2013) has recently emphasized, employment is demand-determined in NK economies and, thus, as DNWR suppresses deflation, it tends to place downward pressure on real interest rates during ZLB episodes, and the associated stimulus to aggregate demand helps support employment, *ceteris paribus*. In our model, DNWR reduces both the probability and severity of ZLB episodes.

These results contribute to at least two important debates currently ongoing in academic and policy circles. First, we highlight an unintended consequence of higher inflation targets, since they tend to mitigate DNWR and thus reduce the aforementioned boost to aggregate demand that DNWR provides during ZLB episodes. As a result, higher inflation targets tend to be associated with more severe ZLB episodes, all else being equal. This suggests that policies that specifically target aggregate demand during ZLB occurrences, such as unconventional monetary policy or fiscal stimulus, may be more effective alternatives to a higher target. Second, frictions that hinder wage adjustment have been traditionally identified as an important source of unemployment, leading to calls for policies aimed at reducing impediments to wage adjustment. Our work, however, supports the emerging idea, proposed by Galí (2013), that wage inflexibility can support employment when monetary policy is constrained by, for example, a currency peg or the ZLB.

These results also echo early contributions from the theory of the second best (Lipsey and Lancaster (1956)): a specific policy that targets a specific distortion may be inappropriate when multiple frictions interact. In the same spirit, Cacciatore et al. (2016), Cacciatore and Fiori (2016), and Eggertsson et al. (2014) have argued more recently that welfare-improving reforms, such as labor and goods markets liberalization, may depress aggregate demand in the short run and involve a costly transition if they are not complemented with expansionary monetary policy.

Our analysis is performed by incorporating two zero lower bounds, one on the nominal interest rate and one on nominal wage growth, in a standard NK model with sticky prices and wages. Monetary policy is represented by a conventional interest rate rule that targets inflation and output fluctuations, as well as the lagged nominal interest rate. The model is solved by applying the piecewise linear perturbation method developed by Guerrieri and Iacoviello (2015). The welfare cost of the ZLB is computed with a linear-quadratic approach (Benigno and Woodford (2012)) over a range of inflation targets between zero and five, and for different combinations of price- and wage-contract duration.[1] We focus on aggregate demand shocks as the main triggers of liquidity traps, following Coibion et al. (2012), Fernández-Villaverde et al. (2015) and Gavin et al. (2015), but the analysis is robust to the inclusion of technology shocks. The model is calibrated so that long-run costs and benefits of inflation at the nonstochastic steady state are nil. However, the model still captures the long-run relation between output and inflation generated by the two occasionally binding constraints and aggregate shocks. The related costs and benefits are fully accounted for by our welfare measure.

Section 2 describes the model; Section 3 discusses the effects of DNWR on the probability of hitting the ZLB and on macroeconomic volatility when liquidity traps occur; Section 4 performs some welfare analysis; and Section 5 concludes. All derivations and robustness checks are relegated to the Appendix.

2. The Model

Consider a closed production economy populated by a continuum of households and firms interacting on goods, labor and asset markets. Households are infinitely lived, have identical preferences over consumption and leisure, and supply a differentiated labor type. Firms produce a differentiated consumption good using as input labor types supplied by all households. Both labor and product markets are monopolistically com-

[1]See Coibion et al. (2012) for an application of this method to a ZLB problem.

petitive, and prices and wages are sticky à la Rotemberg (1982). In addition, nominal wage growth is subject to a zero lower bound, capturing the notion that households and firms might face greater frictions when negotiating wage reductions rather than wage increases.[2] Financial markets are complete and the monetary authority decides on the nominal interest rate in a cashless economy as the one described by Woodford (2003) and Galí (2008). The rest of this section describes the model and its main equilibrium conditions.

2.1. Primitives

Each household $i \in [0,1]$ has preferences defined by

$$U_0^i = E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left(C_t^i\right)^{1-\sigma} - 1}{1-\sigma} - \frac{\left(N_t^i\right)^{1+\varphi}}{1+\varphi} \right] Z_t, \tag{1}$$

where E_0 denotes expectations conditional on information available at time 0, C_t^i and N_t^i denote consumption and hours worked, respectively, $\beta \in (0,1)$ is the subjective discount factor, σ is the inverse intertemporal elasticity of substitution, $\varphi \geq 0$ is the inverse elasticity of labor supply and Z_t is an aggregate preference shock that follows the stochastic process

$$\ln Z_t = \rho_z \ln Z_{t-1} + v_{z,t}, \quad \rho_z \in [0,1). \tag{2}$$

Innovations to the preference shock, $v_{z,t}$, are normal random variables identically and independently distributed with zero mean and variance $\sigma_{v,z}^2$. The flow budget constraint in nominal terms is

$$\begin{aligned} D_t^i + (1+\tau_w) W_t^i N_t^i + \Gamma_t - T_t \quad &- \quad E_t \left\{ Q_{t,t+1} D_{t+1}^i \right\} \geq P_t \left[C_t^i + \Phi_w \left(\Pi_t^{w,i} \right) \right], \\ &\Pi_t^{w,i} \equiv \frac{W_t^i}{W_{t-1}^i}. \end{aligned} \tag{3}$$

Households enter each period with financial wealth D_t^i, earn nominal returns W_t^i on labor, which is subsidized at a rate τ_w, receive dividends distributed by firms Γ_t, pay lump-sum taxes T_t, and buy a portfolio of Arrow-Debreu securities with random nominal value D_{t+1}^i, where $Q_{t,t+1}$ is the one-period-ahead stochastic discount factor.[3] The price of a portfolio paying one unit of currency with certainty, $E_t Q_{t,t+1}$, equalizes the price of risk-free central-bank balances, R_t^{-1}, by a standard no-arbitrage argument.

[2] Adjustment costs can be specified such that if the constraint on nominal wage growth is slack, the model is equivalent to the one in Erceg et al. (2000), who assume Calvo (1983) pricing. Details are provided later in this section.

[3] $Q_{t,t+1}$ is the time-t price vector of state-contingent assets divided by the conditional probability that the state occurs in $t+1$ given information available at t. The general time-t discount factor for nominal payoffs j periods ahead is $Q_{t,t+j} = \prod_{s=t+1}^{t+j} Q_{s-1,s}$.

Income net of savings finances consumption of a final good with price P_t and wage-adjustment costs, expressed in units of the final good. Adjustment costs are modeled as a non-negative, non-decreasing and convex function $\Phi_w(\cdot)$ of household i's wage inflation. Finally, we also assume that nominal wages cannot decrease:

$$\Pi_t^{w,i} \geq 1. \tag{4}$$

Each firm $j \in [0,1]$ produces an intermediate consumption good with a decreasing-return-to-scale technology,

$$Y_{t,j} = X_t N_{t,j}^{1-\alpha}, \quad \alpha \in [0,1), \quad N_{t,j} = \left[\int_0^1 \left(N_{t,j}^i\right)^{\frac{\eta^w - 1}{\eta^w}} di\right]^{\frac{\eta^w}{\eta^w - 1}}, \quad \eta^w > 1, \tag{5}$$

where $N_{t,j}$ aggregates labor types supplied by households and η^w represents the elasticity of substitution between labor types. Shocks to technology, X_t, are identical across firms and evolve according to

$$\ln X_t = \rho_x \ln X_{t-1} + v_{x,t}, \quad \rho_x \in [0,1). \tag{6}$$

Innovations to technology shocks are normal random variables identically and independently distributed with zero mean and variance $\sigma_{v,x}^2$. The present value of current and future nominal profits is

$$E_0 \left\{ \sum_{t=0}^{\infty} Q_{0,t} \Gamma_{t,j} \right\}, \tag{7}$$

$$\Gamma_{t,j} \equiv P_{t,j} Y_{t,j} (1+\tau_p) - \int_0^1 W_t^i N_{t,j}^i di - P_t \Phi_p\left(\Pi_{t,j}\right), \quad \Pi_{t,j} \equiv \frac{P_{t,j}}{P_{t-1,j}}.$$

$P_{t,j}$ is the price of intermediate good j and revenues are subsidized at rate τ_p. Price-adjustment costs are modeled as a non-negative, non-decreasing and convex function $\Phi_p(\cdot)$ of firm j's price inflation, and they are measured in units of the final good, which is a conventional composite index of intermediate goods,

$$Y_t = \left[\int_0^1 \left(Y_{t,j}\right)^{\frac{\eta^p - 1}{\eta^p}} dj\right]^{\frac{\eta^p}{\eta^p - 1}}, \quad \eta^p > 1, \quad P_t \equiv \left[\int_0^1 P_{t,j}^{1-\eta^p} dj\right]^{\frac{1}{1-\eta^p}}, \tag{8}$$

where η^p denotes the elasticity of substitution between intermediate goods.[4] Aggregate profits are finally defined as $\Gamma_t \equiv \int_0^1 \Gamma_{t,j} dj$.

Optimal allocation of households' expenditure across intermediate goods and firms' cost minimization imply demand functions for intermediate goods,

$$Y_{t,j} = \left(\frac{P_{t,j}}{P_t}\right)^{-\eta^p} \left[C_t + \int_0^1 \Phi_w\left(\Pi_t^{w,i}\right) di + \int_0^1 \Phi_p\left(\Pi_{t,j}\right) dj\right], \quad C_t \equiv \int_0^1 C_t^i di, \tag{9}$$

[4] It is equivalent to assume that a competitive retailer buys intermediate goods at prices $P_{t,j}$, produces the consumption good with technology (8) and sells it to households at price P_t, or that households buy each good j at price $P_{t,j}$ to maximize their utility defined over intermediate goods.

and labor,

$$N_t^i = \left(\frac{W_t^i}{W_t}\right)^{-\eta^w} N_t, \qquad W_t \equiv \left[\int_0^1 \left(W_t^i\right)^{1-\eta^w} di\right]^{\frac{1}{1-\eta^w}}, \qquad N_t \equiv \int_0^1 N_{t,j} dj. \tag{10}$$

Households choose the set of state-contingent sequences $\left\{C_t^i, N_t^i, D_{t+1}^i, W_t^i\right\}_{t\geq 0}$ to maximize utility, (1), subject to constraints (3), (4) and (10), taking as given aggregate prices and quantities and initial conditions, D_0^i and W_{-1}^i. Firms choose the set of state-contingent sequences $\{P_{t,j}, Y_{t,j}, N_{t,j}\}_{t\geq 0}$ to maximize profits (7) subject to constraints (5) and (9), taking as given aggregate prices and quantities and the initial condition $P_{-1,j}$.

2.2. Private-sector equilibrium

We focus on symmetric equilibria where $W_t^i = W_t$, $P_{t,j} = P_t$, $\Pi_t^{w,i} = \Pi_t^w$, $\Pi_{t,j} = \Pi_t$ and $D_t^i = 0$, for all t, i and j. Market clearing implies the following feasibility constraints

$$Y_t = C_t + \Phi_w\left(\Pi_t^w\right) + \Phi_p\left(\Pi_t\right), \quad Y_t = X_t N_t^{1-\alpha}, \tag{11}$$

consumption is allocated intertemporally according to a conventional Euler equation,

$$\beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\frac{R_t}{\Pi_{t+1}}\right\} = 1, \quad \Upsilon_t \equiv C_t^{-\sigma} Z_t, \tag{12}$$

and nominal frictions generate NK Phillips curves for price and wage inflation

$$\Phi_p'\left(\Pi_t\right)\Pi_t = \beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\Phi_p'\left(\Pi_{t+1}\right)\Pi_{t+1}\right\} + \eta^p Y_t\left(\left(\mathcal{M}_t^p\right)^{-1} - \frac{\eta^p - 1}{\eta^p}(1+\tau_p)\right), \tag{13}$$

$$\begin{aligned}\Phi_w'\left(\Pi_t^w\right)\Pi_t^w = \beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\left[\Phi_w'\left(\Pi_t^w\right)\Pi_t^w - \Lambda_{t+1}^w\right]\right\} + \Lambda_t^w \\ + \eta^w \frac{W_t}{P_t} N_t\left(\left(\mathcal{M}_t^w\right)^{-1} - \frac{\eta^w - 1}{\eta^w}(1+\tau_w)\right),\end{aligned} \tag{14}$$

with price and wage markups, $\mathcal{M}_t^p$ and $\mathcal{M}_t^w$, defined by

$$\mathcal{M}_t^p \equiv \frac{(1-\alpha)P_t X_t}{W_t N_t^\alpha}, \qquad \mathcal{M}_t^w \equiv \frac{W_t}{P_t N_t^\varphi C_t^\sigma}. \tag{15}$$

The real wage, W_t/P_t, is related to price and wage inflation through identity

$$\frac{W_t}{P_t} = \frac{\Pi_t^w}{\Pi_t}\frac{W_{t-1}}{P_{t-1}}, \tag{16}$$

while Λ_t^w captures the benefit of relaxing constraint (4) and satisfies complementary slackness and non-negativity conditions:[5]

$$\Lambda_t^w \Pi_t^w = 0, \quad \Lambda_t^w \geq 0, \quad \Pi_t^w - 1 \geq 0. \tag{17}$$

A (monopolistically) competitive equilibrium is a set of state-contingent rules,

$$\left\{ N_t, C_t, \Upsilon_t, Y_t, \frac{W_t}{P_t}, \mathcal{M}_t^p, \mathcal{M}_t^w, \Pi_t^p, \Pi_t^w, \Lambda_t^w \right\}_{t\geq 0}, \tag{18}$$

that satisfies equations (11)-(17) given the exogenous state variables, $\{Z_t, X_t\}_{t\geq 0}$, monetary policy, $\{R_t\}_{t\geq 0}$, subsidies, τ_p and τ_w, and the initial condition W_{-1}/P_{-1}. Since taxes are lump-sum, they are immaterial for the equilibrium and for simplicity are set to balance the government budget constraint in every period.

Phillips curves relate price and wage inflation rates to their future expected value and to deviations of markups from their natural level, as in a conventional NK model with sticky prices and wages.[6] However, the wage Phillips curve, (14), differs from that for price inflation by the presence of Λ_t^w, which measures the value of relaxing inequality constraint (4). When the constraint binds, Λ_t^w is strictly positive, signaling that households would like to reduce their relative wage. Since workers fail to internalize the effects of their wage-setting decisions on aggregate demand, eliminating the constraint does not necessarily enhance welfare. Whether this externality makes DNWR socially desirable or not is one of the questions analyzed below.

Λ_t^w has two effects on wage inflation. First, when the constraint binds, wage inflation is higher than it would be in absence of the constraint. Second, if the constraint is expected to bind in the future, workers restrain their wage demands. In fact, the benefit of increasing the current wage is weighed against the cost of being constrained in the future, which is mitigated by dampening current wage inflation.

2.3. Monetary policy

The model is closed by specifying a simple Taylor rule that takes into account the zero lower bound of the nominal interest rate,

$$R_t = \max \left\{ (R_{t-1})^{\gamma_r} \left[\frac{\Pi^T}{\beta} \left(\frac{\Pi_t^p}{\Pi^T} \right)^{\gamma_\pi} \left(\frac{Y_t}{Y} \right)^{\gamma_y} \right]^{1-\gamma_r}, 1 \right\}, \tag{19}$$

where γ_r, γ_π and γ_y are exogenously given Taylor-rule coefficients, Π^T is an exogenously given inflation target and Y denotes the level of output at the non-stochastic steady state. This rule implies inflation rates $\Pi^p = \Pi^w = \Pi^T$ at the non-stochastic steady state.

[5]See the Appendix for a formal definition of Λ_t^w, which is proportional to the Lagrange multiplier attached to equation (4).

[6]Natural values of price and wage markups are $\eta^p/((\eta^p - 1)(1 + \tau_p))$ and $\eta^w/((\eta^w - 1)(1 + \tau_w))$, respectively, and they are obtained by imposing $\Phi_p(\cdot) = 0$, $\Phi_w(\cdot) = 0$ and $\Lambda_t^w = 0$.

2.4. A canonical representation

A useful benchmark is given by the natural equilibrium, where both prices and wages are fully flexible, upwards and downwards, which can be obtained by imposing $\Phi_p = \Phi_w = \Lambda_t^w = 0$. The natural values of output, hours worked and the real wage in log deviations from the non-stochastic steady state are

$$y_t^n = \Psi_y x_t, \quad n_t^n = \frac{(1-\sigma)\Psi_y}{1+\varphi} x_t, \quad \omega_t^n = \frac{(\sigma+\varphi)\Psi_y}{1+\varphi} x_t, \quad \Psi_y \equiv \frac{1+\varphi}{\sigma(1-\alpha)+\varphi+\alpha}. \tag{20}$$

Two features of the natural equilibrium are important. The level of employment depends only on technology shocks. Hence, equilibrium fluctuations in hours worked and output, conditional on preference shocks, signal inefficient variations in markups. In addition, for the limiting case of logarithmic utility in consumption, *any* fluctuation in employment is inefficient.

Another relevant benchmark is the standard NK model with sticky prices and wages as in Erceg et al. (2000) or Galí (2008), which can be recovered as a particular case of our framework under some parametric assumptions. First, assume that price- and wage-adjustment costs are negligible at a first-order approximation and nil at the non-stochastic steady state, i.e.,

$$\Phi_p(\Pi) = \Phi_w(\Pi^w) = \Phi_p'(\Pi) = \Phi_w'(\Pi^w) = 0. \tag{21}$$

In addition, choose subsidies to offset monopolistic distortions,

$$\tau_p = \frac{1}{\eta^p - 1}, \qquad \tau_w = \frac{1}{\eta^w - 1}, \tag{22}$$

so that the steady-state levels of output, hours worked and the real wage are Pareto efficient and coincide with their natural counterpart. Then, a first-order approximation of equations (13)-(16) yields[7]

$$\widehat{y}_t = E_t \widehat{y}_{t+1} - \frac{1}{\sigma}\left[r_t - E_t\pi_{t+1} - r_t^n\right], \quad r_t^n \equiv (1-\rho_z)z_t - \sigma(1-\rho_x)\Psi_y x_t, \tag{23}$$

$$\pi_t = \beta E_t \pi_{t+1} + \frac{\alpha\delta^p}{(1-\alpha)}\widehat{y}_t + \delta^p \widehat{\omega}_t, \quad \delta^p \equiv \frac{\eta^p Y}{\Phi_p'' \Pi^2}, \tag{24}$$

$$\pi_t^w = \beta E_t\left(\pi_{t+1}^w - \delta^w \lambda_{t+1}^w\right) + \delta^w\left[\left(\sigma + \frac{\varphi}{1-\alpha}\right)\widehat{y}_t - \widehat{\omega}_t + \lambda_t^w\right], \delta^w \equiv \frac{\eta^w W N}{P\Phi_w''(\Pi^w)^2}, \tag{25}$$

$$\widehat{\omega}_t = \widehat{\omega}_{t-1} + \pi_t^w - \pi_t - \Delta\omega_t^n, \tag{26}$$

[7]Lower-case variables denote log deviations from the non-stochastic steady state, with the only exception of the real wage, $\omega_t \equiv log(W_t/P_t) - log(W/P)$, and $\lambda_t^w \equiv (\Lambda_t^w - \Lambda^w)P/(\eta^w WN)$. Arguments of functions $\Phi_p''(\Pi)$ and $\Phi_w''(\Pi^w)$ have been suppressed for notational convenience.

after defining the output gap, $\widehat{y}_t = y_t - y_t^n$, the real wage gap, $\widehat{\omega}_t = \omega_t - \omega_t^n$, and where r_t^n denotes the natural real interest rate. Finally, calibrate adjustment cost functions as

$$\begin{aligned} \Phi_p'' &= \frac{\theta^p(1-\alpha+\alpha\eta^p)\eta^p Y}{(1-\alpha)(1-\theta^p)(1-\theta^p\beta)\Pi^2}, \\ \Phi_w'' &= \frac{\theta^w(1+\varphi\eta^w)\eta^w\omega N}{(1-\theta^w)(1-\theta^w\beta)\left(\Pi^w\right)^2}. \end{aligned} \tag{27}$$

If $\lambda_t^w = 0$, our model coincides at a first-order approximation with the standard NK model with sticky prices and wages, where θ^p and θ^w represent the time-t probabilities that intermediate goods and labor services, respectively, cannot be repriced.[8] Hence, if $R_t > 1$ as well, the equilibrium is the same as in Erceg et al. (2000) and Galí (2008).

In the full-blown version of the model, the inequality constraint $\pi_t^w \geq -\pi_w$ is allowed to bind occasionally and $\lambda_t^w \geq 0$. If assumptions used to derive equations (23)-(26) are maintained, and irrespective of whether the zero lower bounds are occasionally binding or not, a second-order approximation of the utility function yields[9]

$$\mathbb{W} = -\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left\{\left(\sigma+\frac{\varphi+\alpha}{1-\alpha}\right)\widehat{y}_t^2+\frac{\eta^p}{\delta^p}\pi_t^2+\frac{\eta^w(1-\alpha)}{\delta^w}\left(\pi_t^w\right)^2\right\}, \tag{28}$$

which coincides with the welfare criterion obtained by Erceg et al. (2000) and Galí (2008). Since the function is purely quadratic, a piecewise linear approximation of the equilibrium is enough to characterize welfare at second-order accuracy.

2.5. Solution method and parameterization

The economy features two constraints that bind occasionally so standard-perturbation techniques cannot be applied. The model is solved with the piecewise linear perturbation method developed by Guerrieri and Iacoviello (2015). The method handles inequality constraints as different regimes of the same model, where regimes are defined by whether the constraints are binding or not. While the dynamics of each regime are solved linearly, expectations are computed by taking into account the fact that the probability of switching across regimes is endogenous. The interaction between the

[8]Expression (27) extends the known similarity between Calvo (1983) and Rotemberg (1982) pricing pointed out by Khan (2005) and Ascari et al. (2011) to the case of sticky wages.

[9]Inequality constraints induce non-differentiability of decisions rules (18). Notice, however, that a second-order Taylor expansion of utility is well defined because the expressions needed to derive (28) – the utility function (1) and feasibility constraints (11) – are differentiable, while neither the inequality constraint, (4), nor the Taylor-type rule, (19), need to be used in the approximation. For an application of this method to a ZLB problem see Coibion et al. (2012). They also compare piecewise linear perturbation with higher-order methods without finding quantitatively significant differences in impulse response functions. Even though our model is similar – and much simpler – the usual disclaimer that accuracy may be model specific applies.

state of the economy and the expected duration of regimes captures the non-linear effects due to the constraints. However, the approximation remains linear conditional on the probability of switching across regimes and cannot account for precautionary behavior. As an implication, the model can explain wage restraint aimed at moderating the expected cost – but not the risk – of being bound by DNWR in the future.

Parameter values are primarily borrowed from the existing literature on DNWR and/or the ZLB and are summarized in Table 1. The discount factor, Taylor-rule coefficients, the technology parameter α, and the elasticity of substitution between goods and labor types are chosen from Kim and Ruge-Murcia (2009).[10] The intertemporal elasticity of substitution and the Frisch elasticity of labor supply are assumed to be equal to one. The serial correlation of technology is set to 0.9, while its standard deviation, 0.25 percent, reflects the lower volatility of labor productivity in the last two decades (Fernández-Villaverde et al. (2015)). Shocks to preferences can be reinterpreted as a wedge between the policy rate, r_t, and the cost of borrowing, $r_t + q_t$,

$$c_t = E_t c_{t+1} - \frac{1}{\sigma}\left[r_t + q_t - E_t \pi_{t+1}\right], \qquad q_t \equiv -(1-\rho_z) z_t, \tag{29}$$
$$q_t = \rho_z q_{t-1} + v_{q,t}, \quad v_{q,t} = -(1-\rho_z) v_{z,t},$$

where equation (29) follows directly from the log-linearized Euler equation (23). Exogenous fluctuations in the spread q_t capture shocks to aggregate demand due to changes in financial conditions. Persistence and standard deviation of the preference shock are set to match the values for the half-life and the standard deviation of q_t assumed by Guerrieri and Iacoviello (2015).

The rest of this paper maintains parametric assumptions (21) and (22). We primarily focus on the case of upward flexible wages ($\Phi_w(\cdot) = 0$) to highlight the role of DNWR, while price duration is set to two quarters. Unless otherwise stated we maintain this calibration, but we also consider a variety of combinations of price- and wage-contract durations to explore the interaction between nominal rigidities and the ZLB. For given durations, parameters $\Phi_w''(\Pi^w)$ and $\Phi_p''(\Pi)$ are chosen according to expression (27). The inflation target is varied between 0 and 4.5 percent.

In our study we focus on preference shocks for two reasons. First, technology shocks cannot account for ZLB episodes in a standard NK model because they have the implication of generating economic booms during liquidity traps. Second, in this framework an adverse demand shock may be interpreted as limited access to credit so it may capture one of the purported sources of the Great Recession and associated ZLB episodes. While we focus on demand shocks for calculating welfare, we include both preference and technology shocks when we compute the unconditional probability that the ZLB binds.

[10]The discount factor is equal to the mean of the inverse ex-post real interest rate in the United States between 1964 and 2006. The short-run response of the nominal interest rate to inflation and output are $(1-\gamma_r)\gamma_\pi = 1.176$ and $(1-\gamma_r)\gamma_y = 0.068$, which coincide with the estimates by Kim and Ruge-Murcia (2009).

It is well known that DNWR is costly conditional on technology shocks when the ZLB does not bind and, even if the central bank optimally addresses business cycle fluctuations, a moderately positive inflation target reduces its incidence and improves welfare (Kim and Ruge-Murcia (2009)). While the cost of DNWR might be underestimated because of the omission of technology shocks, the Appendix shows that their inclusion does not affect our conclusions.

3. The ZLB, DNWR and Macroeconomic Volatility

The first portion of this section analyzes the effects of DNWR on the frequency and duration of ZLB episodes while the second subsection examines the severity of ZLB occurrences in terms of macroeconomic outcomes. To this end, four alternative versions of the model are considered. The standard NK model with sticky prices and wages assumes away all lower bounds. One extension augments the standard model with downward nominal wage rigidity and is referred to as the DNWR model. Another, labeled the ZLB model, adds the zero bound on the nominal interest rate to the NK model. The final version includes both downward nominal wage rigidity and the zero bound on the nominal interest rate and is known as the ZLB-DNWR model. All versions are simulated for $15,000$ periods with the same random draw of innovations. Simulations are used to compute the probability and duration of ZLB episodes, as well as business cycle moments, both unconditional and conditional on the ZLB.

3.1. Frequency and duration of the ZLB under DNWR

The analysis begins by examining the relative contribution of technology and preference shocks in triggering episodes at the zero bound in the ZLB and ZLB-DNWR models (Figure 1). The unconditional distribution of shocks lie symmetrically within three standard deviations of their mean. In both models, the distributions conditional on the ZLB are shifted as compared with the unconditional distributions, to the right for the case of technology shocks (upper panel) and to the left for the case of preference shocks (lower panel). The shift is more pronounced for preference than for technology shocks: this result suggests that the former are more important in generating ZLB incidents under our calibration. Moreover, a comparison of the conditional distributions generated by the ZLB and ZLB-DNWR models reveals that the latter requires larger shocks for liquidity traps to occur, suggesting that DNWR reduces the probability of hitting the ZLB.

Coibion et al. (2012) were the first to notice that the presence of DNWR reduces the probability of hitting the ZLB. Their intuition follows from the idea that DNWR induces the real marginal cost to be downward rigid, which moderates the decline in inflation resulting from a negative demand shock. As a consequence, the response of monetary policy is attenuated and the likelihood of reaching the zero bound is lessened. The graphs in the upper panel of Figure 2 corroborate this result. For example, at a 1 percent inflation target, the frequency of hitting the zero bound is about 25 percent when the ZLB is considered in isolation. In contrast, the same frequency falls to only 10 percent when the model incorporates both the ZLB and DNWR.

While Coibion et al. (2012) focus on the likelihood of reaching the ZLB, we also uncover a novel result concerning DNWR's impact on the duration of ZLB episodes. Since the presence of DNWR moderates downward movements in the real marginal cost, expected inflation is also higher relative to the case without DNWR. As a result, the real interest rate is lower than otherwise and, thereby, provides more monetary stimulus, leading to a shorter spell at the ZLB. This result can be seen in the lower panels in Figure 2. From the figure, it is readily apparent that the presence of DNWR reduces the average duration of zero bound episodes relative to a model with only the ZLB, with the gap widening at lower rates of inflation. With a 1 percent inflation target, for example, the mean duration of a zero bound spell falls from almost 4 quarters in the ZLB model to 2.5 quarters in the ZLB-DNWR model.

Overall, our analysis suggests that DNWR, through an extensive margin, reduces the frequency of ZLB incidents and at the same time lowers the average duration of a spell at the zero bound via an intensive margin.

3.2. DNWR and the severity of ZLB episodes

DNWR and the ZLB considered in isolation prevent an economy from efficiently responding to shocks and, therefore, entail some output loss. As shown in the previous section, however, DNWR can shorten the duration of ZLB occurrences. In this section, we examine the macroeconomic impact of the ZLB when DNWR is present.

We start by comparing the dynamic response of the two models without the zero bound (i.e., the baseline and DNWR models with the inflation target set to two) to a preference shock large enough to make the DNWR bind. Figure 3 reports impulse response functions for selected variables across the two models. Comparing the responses, we see the presence of DNWR prevents nominal wages from falling rapidly as in the standard NK model, leading to a more restrained response in price inflation and nominal interest rates (despite the omission of the ZLB in this experiment). As a result, the real interest rate is higher in the DNWR model, and consumption and hours worked are lower.

Figure 4 repeats the exercise for the two models that account for the ZLB. A comparison of the ZLB model to the NK model (reported in Figure 3) shows how the ZLB amplifies the adverse consequences of the shock. In particular, consumption and hours worked decline significantly when the nominal interest rate cannot fall below zero. That is, the central bank is unable to provide the economy with sufficient monetary stimulus via its policy rate, relative to the standard model, which abstracts from the ZLB.

Even though DNWR and the ZLB have deleterious effects when taken in isolation, Figure 4 shows that DNWR mitigates the adverse effects of a negative demand shock that forces the economy to the ZLB. Relative to the model that accounts only for the ZLB, the decline in consumption and hours worked is smaller and the nominal interest rate is at its zero bound for fewer periods. The attenuating effect arises from the ability of DNWR to moderate wage disinflation and, thereby, price disinflation, which leads to a more muted response of the real wage and a lower real interest rate. Both results help support aggregate demand and reduce the output loss associated with being at the ZLB.

Table 2 displays selected simulated moments for both models. In line with the impulse response analysis, two main facts stand out. All volatilities – unconditional and conditional on hitting the ZLB – are lower if wages are downward rigid. Figure 5 confirms that macroeconomic volatility is always lower in the ZLB-DNWR model, unless price inflation is large enough to make DNWR irrelevant. In addition, the output gap and inflation rates are higher on average, both unconditionally and when the ZLB binds. Hence, even if the model is calibrated in such a way that the Phillips curve is vertical at the non-stochastic steady state, the stochastic economy displays a positively sloped long-run Phillips curve because of the occasionally binding constraints. Figure 6 confirms that this is the case and reveals that the model with rigid wages systematically predicts less negative output gaps.

At first pass, it seems surprising that wage rigidity contains rather than amplifies inefficient fluctuations. Indeed, some believe that if wages lie above their competitive level, employment must be inefficiently low. However, as emphasized by Galí (2013), this logic follows from the assumption that goods prices are fully flexible and aggregate demand is irrelevant for employment. The logic is reversed when goods prices are sticky, because employment becomes demand-determined. Figure 7 compares the behavior of employment in the ZLB and in the ZLB-DNWR models for different combinations of price and wage rigidity, when the economy is hit by a two-standard-deviation negative preference shock. If prices and wages are fully flexible (top-left quadrant), the ZLB is irrelevant for quantities and employment inefficiently falls only when DNWR is introduced. The pattern, however, inverts when other nominal rigidities are present.

As expected, Figure 7 also documents that an increase in wage adjustment costs renders DNWR less relevant, as compared with the standard NK model that already incorporates symmetric wage adjustment costs.

Building on these results, one might guess that the benefits of deviating from price stability to take care of the ZLB are overestimated if DNWR is neglected. We thus turn to welfare analysis in Section 4.

3.3. DNWR and the "missing disinflation"

In the aftermath of the recent financial crisis, output growth in many advanced economies weakened but without a commensurate decline in inflation. In fact, it seemed that the fundamental positive relationship between inflation and the level of economic activity posited by many macroeconomic theories had been brought into question. Our results add some insights to this question.

The behavior of nominal wage inflation in Figure 4 shows that the model also captures pent-up wage deflation. Under the assumption of flexible wages, wage inflation massively falls on impact and it rises as soon as the demand shock starts dissipating. In the model with DNWR instead, nominal wages fall by less initially, but they also recover with a delay. This is because of two forces: on the one hand, DNWR leaves real wages higher than they would normally be, eliminating the need to readjust them upwards during the recovery; on the other hand, positive expected values of λ^w_{t+1} discourage households from negotiating higher wages to contain the future cost of being constrained. As in Daly and Hobijn (2014), DNWR also tempers wage increases. Faced with such a result, it is natural to ask whether the reverse also holds, i.e., whether upward nominal wage rigidity affects the likelihood of wage cuts.

Figure 8 displays impulse responses to a negative preference shock of two standard deviations in the ZLB-DNWR model for different durations of wage contracts, while price duration is kept constant and equal to two quarters. In all cases, wage inflation hits its lower bound on impact, but the larger the wage adjustment cost, the faster nominal wage growth recovers. At first counterintuitive, the finding follows from the fact that if wages are stickier upwards, both the current and the future value of relaxing the constraint on nominal wage growth fall. Hence, households become less reluctant in negotiating higher wage increases and pent-up wage deflation loses relevance. This finding suggests that rigidity upwards is welfare detrimental because it partially offsets the beneficial effects of rigidity downwards. A recently emphasized monetary policy implication of pent-up wage deflation is that the central bank might be misled and withdraw monetary accommodation too late if the lack of wage inflation was interpreted as signaling labor market slack. This concern is, however, tempered if wages are upward rigid. Since the incidence of DNWR, and thus of pent-up wage deflation, depends on the duration of wage contracts, studying the two frictions separately might be misleading.

4. DNWR and the cost of the ZLB

All variants of the model share the same non-stochastic steady state irrespective of monetary policy, so that equation (28) can be used to rank alternative policies as well as to compute the welfare cost of the ZLB.

The expected cost of the ZLB, both in the ZLB and in the ZLB-DNWR models, is computed as the fraction of steady-state consumption that households would be willing to give up in order to switch to the NK and to DNWR model, respectively.[11] The total expected cost of the ZLB reflects both differences in the frequency of ZLB episodes as well as differences in the welfare cost of an average ZLB quarter. Since the frequency of the ZLB varies across models, it may be informative to compute the cost of the ZLB per quarter spent at the zero bound, which is obtained by dividing the total expected cost by the unconditional probability of hitting the ZLB in any given quarter (Coibion et al. (2012)). Figure 9 reports those numbers.

[11]Equation (28) measures welfare directly in terms of consumption equivalents because the approximation has been re-scaled by $(\partial U/\partial C)C$.

In the ZLB model, as expected, both costs fall in the inflation target. As average inflation rises, the likelihood of hitting the zero bound diminishes. In addition, even if the shock is large enough to force the economy into a zero bound spell, inflation gives the central bank enough latitude to cut the policy rate and make the consequent recession milder. Therefore, the per-quarter cost also falls.

Inflation also reduces the total cost of the ZLB in the ZLB-DNWR model. However, the cost is uniformly smaller than in the ZLB model, because DNWR alone mitigates the likelihood of hitting the zero bound. In addition, increasing the inflation target becomes less effective because it also diminishes the incidence of DNWR, which is in turn useful to prevent the occurrence of zero bound events. Hence, the cost is flatter with respect to the inflation target, which is not an important factor for the cost of hitting the zero bound.

In addition, DNWR acts through an intensive margin, making occurrences at the ZLB less severe should they materialize. For this reason, the cost per ZLB quarter becomes U-shaped. Starting from the case of zero inflation, it initially falls as in the case without downward nominal wage rigidity. However, as the inflation target increases DNWR becomes less relevant and, given that it moderates the adverse effects of the ZLB, the cost per quarter starts rising. Overall, increasing the inflation target in the presence of DNWR seems to make ZLB episodes less recurrent but more costly, leaving their total expected cost roughly unaffected.

Figure 5 summarizes the gains of DNWR in reducing the cost of the ZLB for alternative calibrations of price and wage duration. Gains are sizeable: for a 2 percent percent inflation target, which already eliminates the incidence of DNWR to a large extent, gains still range from 0.05 to 0.20 percent of steady-state consumption, depending on the duration of price and wage contracts. Figure 5 confirms that these gains would survive the use of an ad-hoc, and more conventional, welfare function that abstracts from wage inflation.

5. Concluding remarks

This paper studies how DNWR interacts with the ZLB and the implications of such an interaction for the inflation target. We contribute to the recently revived literature on DNWR in three respects. First, the conclusion that DNWR is responsible for inefficient employment fluctuations when monetary policy is constrained by the ZLB heavily relies on the assumption that the economy is not subject to any other distortion. Hence, it is not robust to the introduction of nominal price rigidities, nor of upwardly sticky wages. Second, DNWR might be an important part of the puzzling missing disinflation witnessed during the Great Recession. Finally, the presence of DNWR alone is not sufficient to argue in favor of a higher inflation target as long as the current target adequately addresses concerns regarding the ZLB.

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Table 1: Benchmark parameterization

Description	Parameter	Value
Discount factor	β	0.997
Risk aversion	σ	1
Labor supply elasticity	φ	1
Technology parameter	α	1/3
Elasticity of substitution of goods	η^p	11
Elasticity of substitution of labor types	η^w	3.5
Interest rate smoother	γ_r	0.381
Taylor coefficient on inflation	γ_π	1.89
Taylor coefficient on output	γ_y	0.11
Serial correlation of technology shocks	ρ_x	0.9
Std. deviation of innovations to technology shocks	$\sigma_{v,x}$	0.25%
Serial correlation of demand shocks	ρ_u	0.8
Std. deviation of innovations to demand shocks	$\sigma_{v,u}$	2%

Table 2: Comparison of moments in the ZLB and ZLB-DNWR models conditional on demand shocks and for alternative durations of price and wage contracts. The inflation target is set to 2%; the Flex wage calibration assumes upward flexible wages and a two-quarter price duration. The 2Q wage duration calibration assumes a two-quarter duration for both prices and wages. The Flex price calibration assumes flexible prices and a two-quarter wage duration. Price and wage inflation and the nominal interest rates are annualized.

	Flex wage		2Q wage duration		Flex price	
	ZLB	ZLB-DNWR	ZLB	ZLB-DNWR	ZLB	ZLB-DNWR
ZLB Frequency	14.27%	9.65%	10.51%	8.75%	15.30%	12.75%
Unconditional moments						
Std. deviation of the output gap	1.20%	0.88%	1.12%	1.00%	1.11%	0.79%
Std. deviation of price inflation	2.64%	1.48%	1.59%	1.27%	3.64%	1.86%
Std. deviation of wage inflation	7.16%	2.75%	2.20%	1.62%	3.36%	1.65%
Std. deviation of nominal interest rate	2.68%	2.62%	2.38%	2.35%	2.86%	2.83%
Mean output gap	-0.19%	-0.17%	-0.10%	-0.10%	-0.23%	-0.18%
Mean price inflation	1.70%	2.17%	1.92%	2.06%	1.49%	2.08%
Mean wage inflation	1.70%	2.17%	1.92%	2.06%	1.49%	2.08%
Mean nominal interest rate	3.45%	3.59%	3.36%	3.40%	3.57%	3.60%
Moments at the ZLB						
Std. deviation of the output gap	2.05%	1.08%	1.61%	1.06%	1.93%	1.06%
Std. deviation of price inflation	3.85%	0.38%	1.70%	0.37%	5.73%	0.94%
Std. deviation of wage inflation	14.37%	0%	2.95%	0.02%	5.10%	0.03%
Mean output gap	-2.14%	-1.99%	-2.21%	-2.16%	-2.01%	-1.63%
Mean price inflation	-2.70%	-0.09%	-1.07%	-0.06%	-4.34%	-0.82%
Mean wage inflation	-5.05%	0.01%	-1.81%	0.01%	-3.96%	0.01%

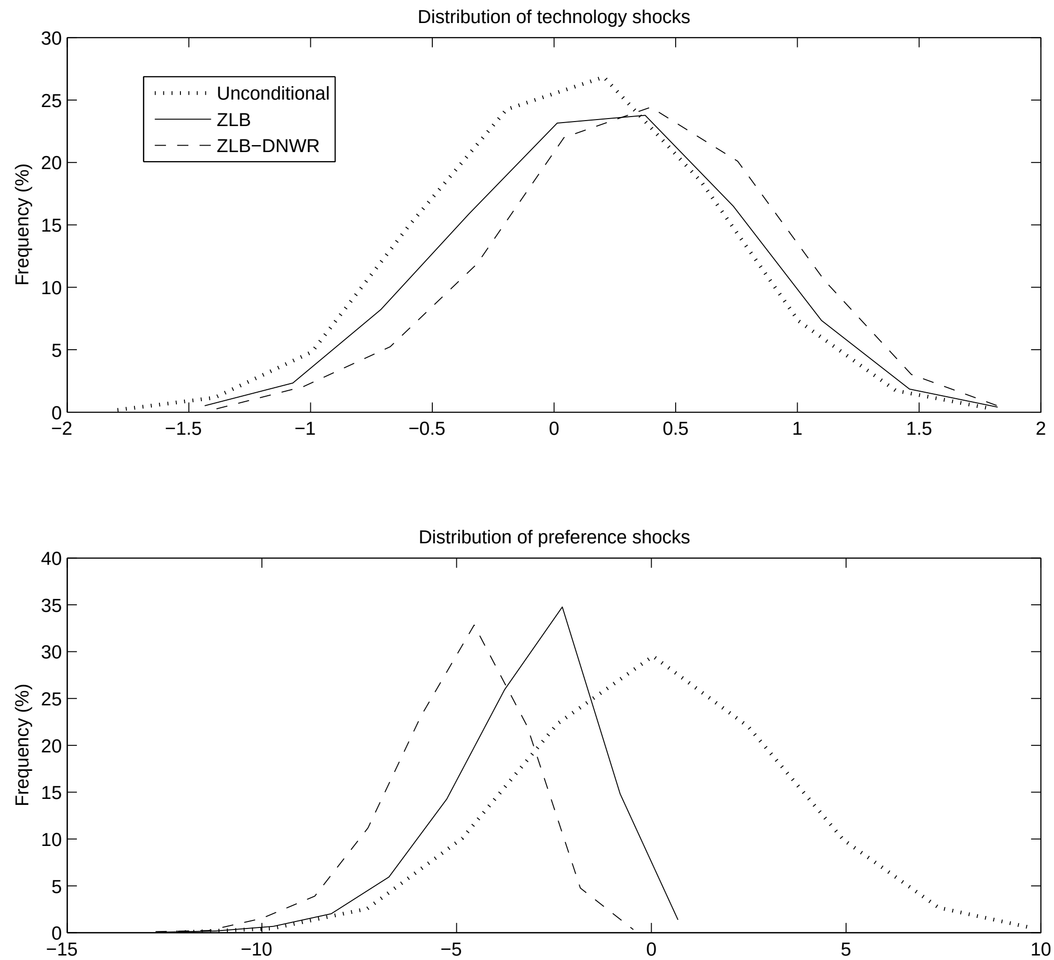

Figure 1: Unconditional distributions of technology and preference shocks, and distributions conditional on the ZLB being binding. Solid lines refer to the ZLB model, while dashed lines refer to the ZLB-DNWR model. The top panel reports technology shocks and the bottom panel reports demand shocks. The inflation target is set to 0 and the value of shocks, reported on the horizontal axis, is measured in percentage deviations from the unconditional mean.

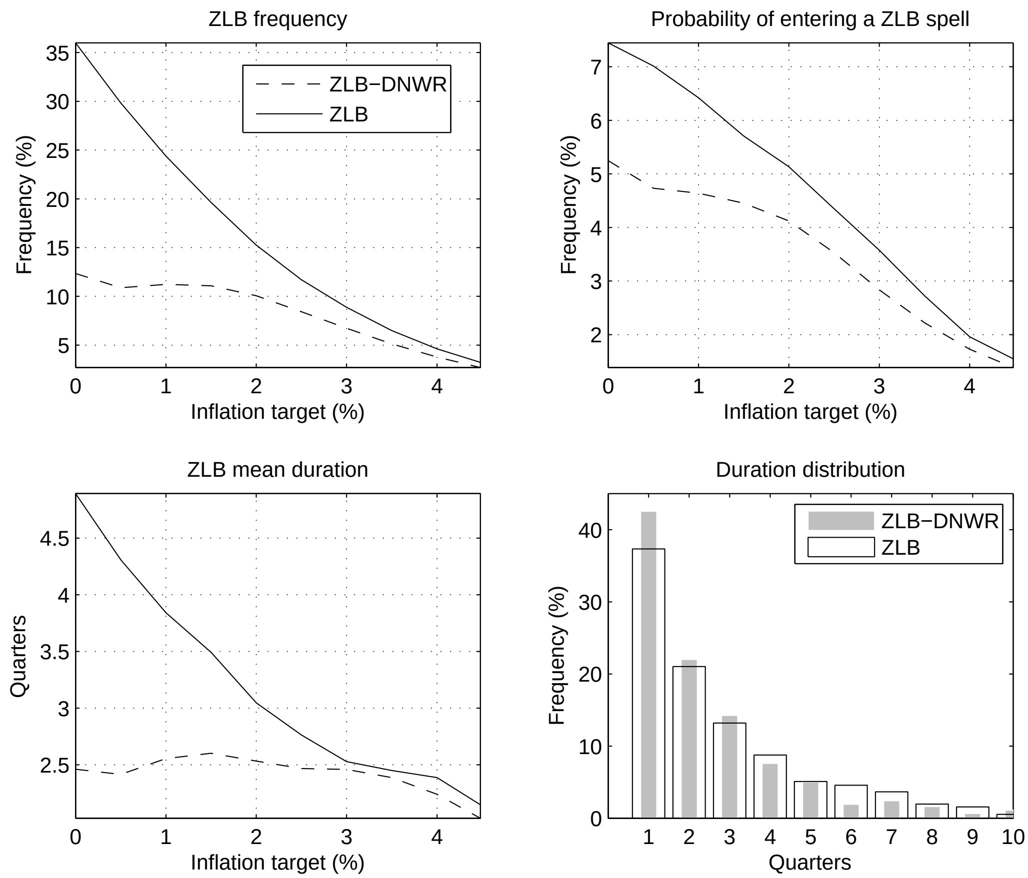

Figure 2: ZLB statistics in the ZLB-DNWR and ZLB models. The ZLB frequency (top-left panel) is defined as the share of quarters spent at the ZLB as a function of the inflation target. The probability of entering a ZLB spell (top-right panel) is computed as the share of quarters that a ZLB spell starts, irrespective of its duration. The ZLB mean duration (bottom-left panel) is the average duration of ZLB spells measured in quarters. The frequency of spells by duration (bottom-right panel) plots the share of spells of a given length as a fraction of the total number of spells for the case of a zero inflation target.

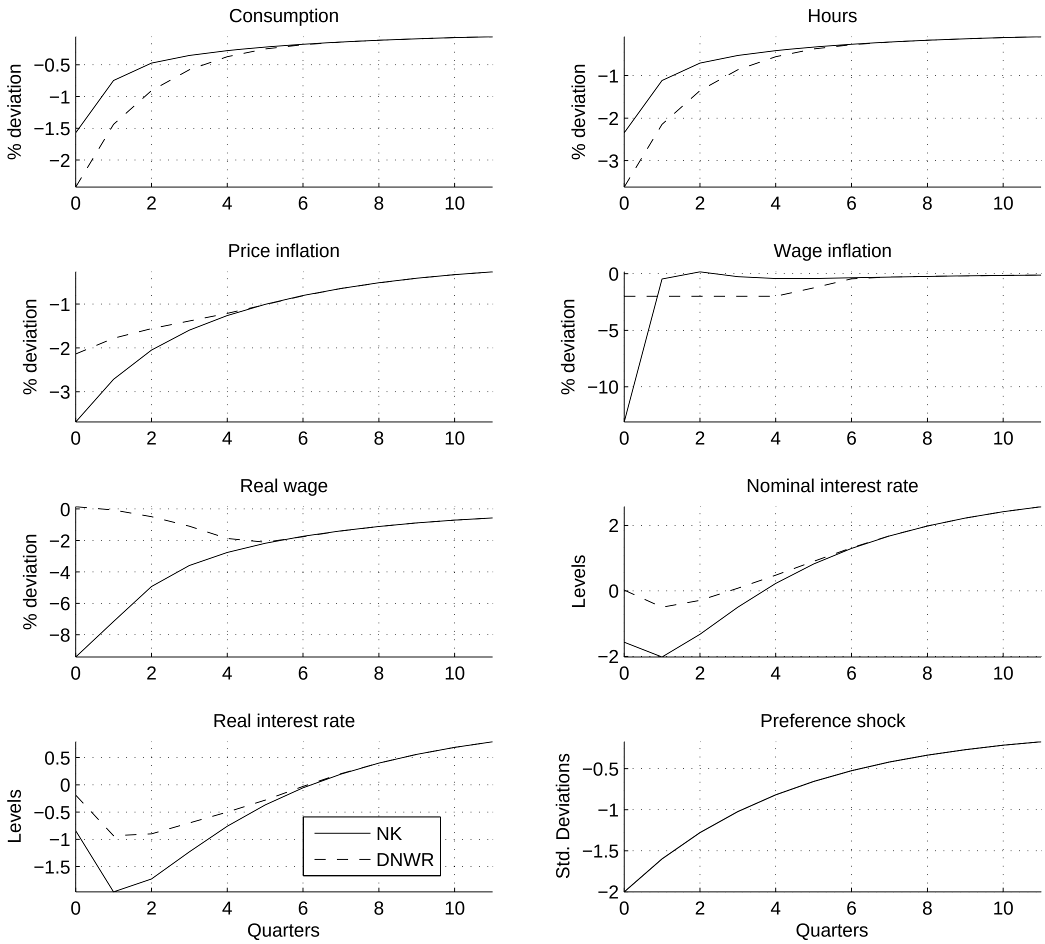

Figure 3: Impulse response functions of selected variables to a two-standard-deviation negative preference shock in the NK (solid lines) and DNWR (dashed lines) models. Nominal and real interest rates are expressed in percentage and annualized. Price and wage inflation are expressed in percentage, annualized and reported in deviation from their steady-state value. All other variables are reported in percentage deviations from the steady state. The inflation target is set to 2%.

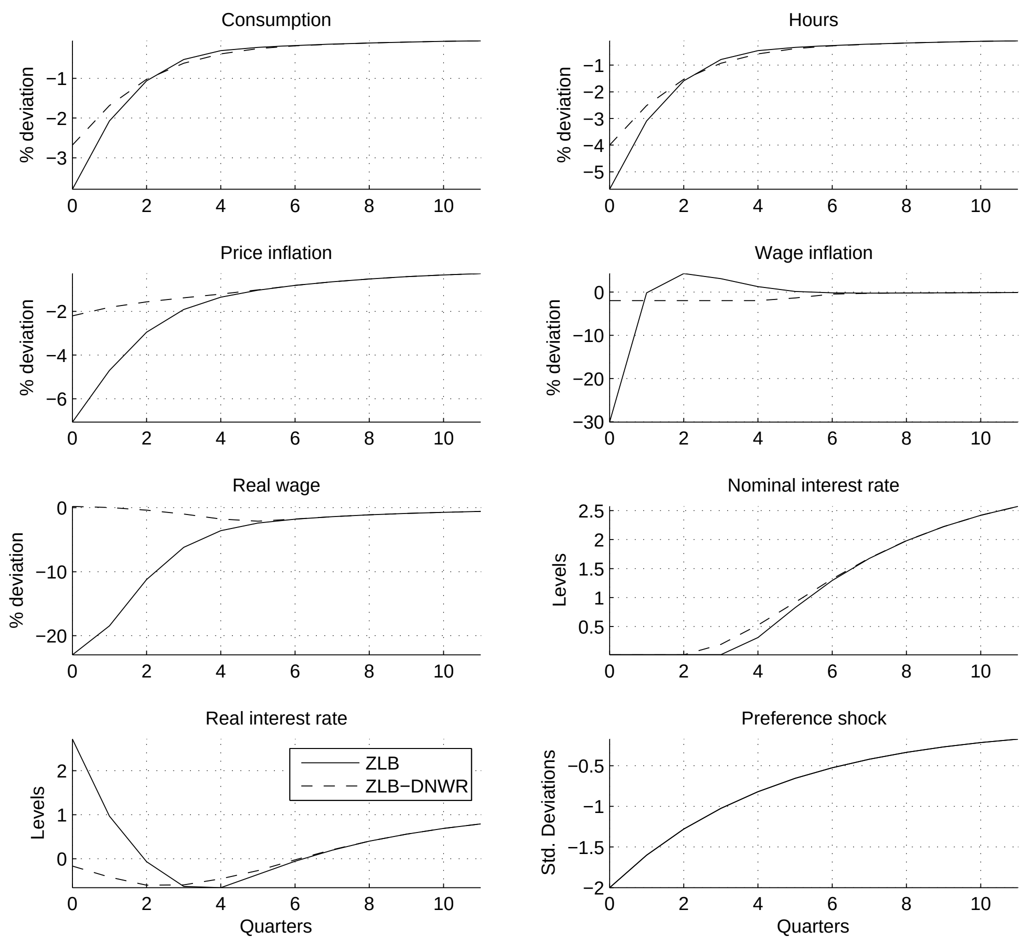

Figure 4: Impulse response functions of selected variables to a two-standard-deviation negative preference shock in the ZLB (solid lines) and ZLB-DNWR (dashed lines) models. Nominal and real interest rates are expressed in percentage and annualized. Price and wage inflation are expressed in percentage, annualized and reported in deviation from their steady-state value. All other variables are reported in percentage deviations from the steady state. The inflation target is set to 2%.

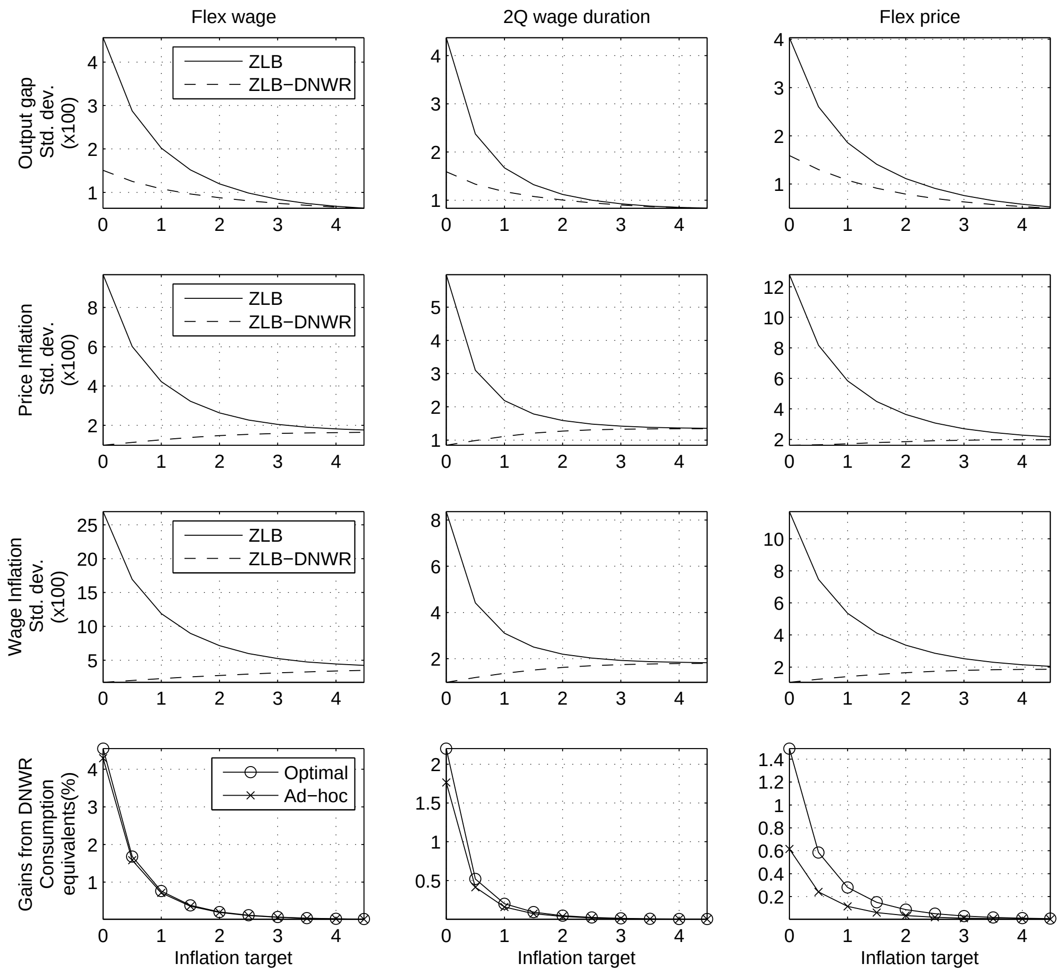

Figure 5: Standard deviations and welfare in the ZLB (solid lines) and in the ZLB-DNWR (dashed lines) models as a function of the inflation target. Inflation rates are annualized and the output gap is quarterly. Gains from DNWR are computed by subtracting the cost of the ZLB in the ZLB-DNWR model from the cost of the ZLB in the ZLB model. "Optimal" denotes the cost computed with the micro-founded welfare function. "Ad-hoc" denotes the cost computed with a loss function that assigns no weight to wage inflation. The flex wage calibration assumes that wages are flexible upwards and prices have a two-quarter duration. The 2Q wage duration calibration assumes a two-quarter duration for both prices and wages. The flex price calibration assumes flexible prices and a two-quarter wage duration.

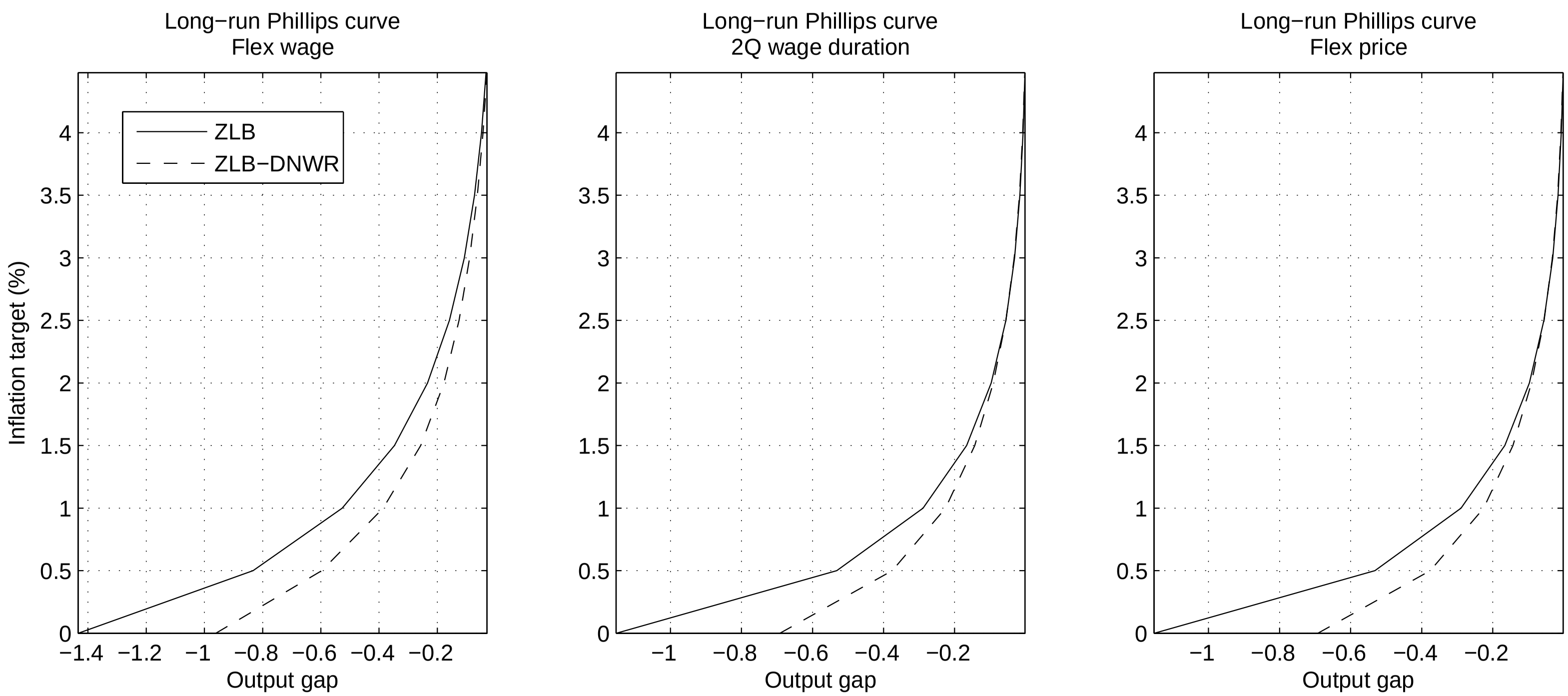

Figure 6: Long-run Phillips curve. The Flex wage calibration assumes upward flexible wages and a two-quarter price duration. The 2Q wage duration calibration assumes a two-quarter duration for both prices and wages. The Flex price calibration assumes flexible prices and a two-quarter wage duration.

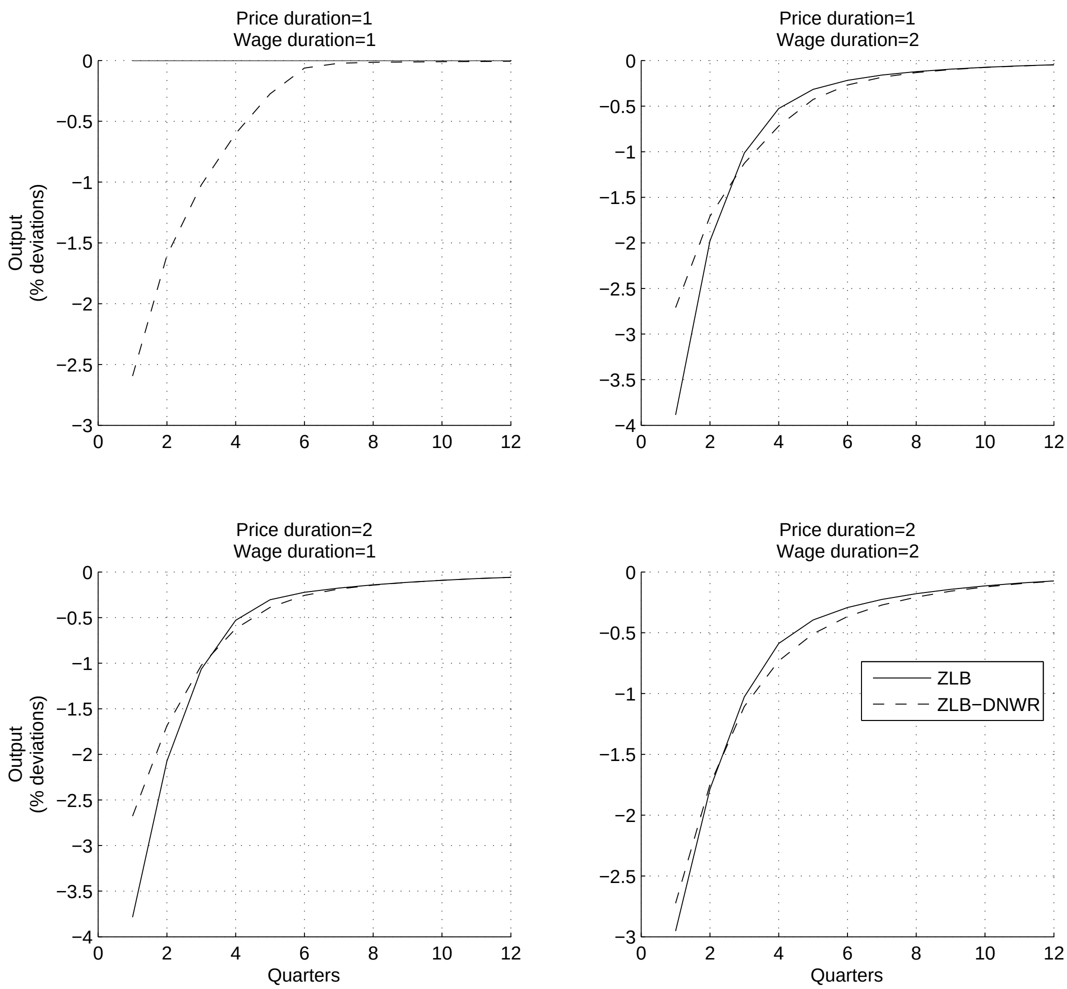

Figure 7: Response of output for different combinations of price and wage rigidity when the economy is hit by a negative preference shock of two standard deviations. The inflation target is set to 2%. Dashed (solid) lines refer to the ZLB-DNWR (ZLB) model.

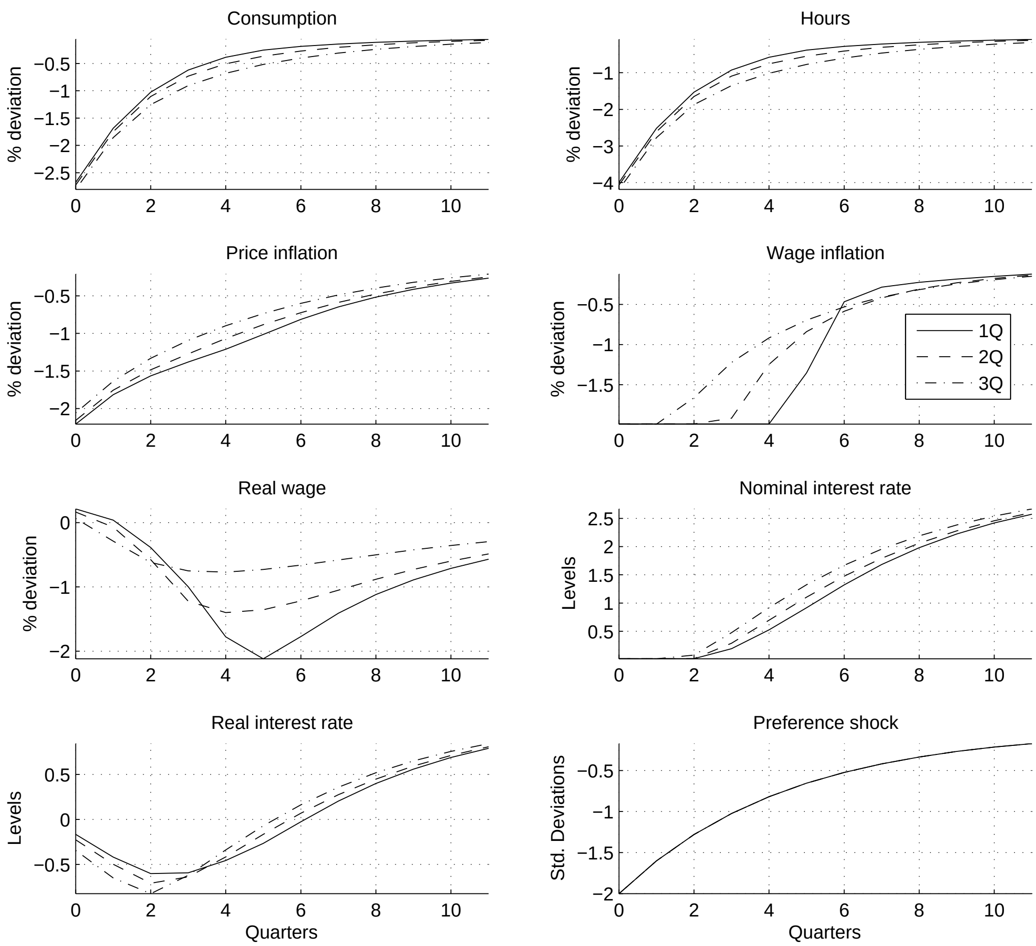

Figure 8: Impulse response functions of selected variables to a two-standard-deviation negative preference shock in the ZLB-DNWR model for alternative durations of wage contracts. 1Q, 2Q and 3Q stand for one-quarter, two-quarter and three-quarter duration of wage contracts. The duration of price contracts is maintained to two quarters. Nominal and real interest rates are expressed in percentage and annualized. Price and wage inflation are expressed in percentage, annualized and reported in deviation from their steady-state value. All other variables are reported in percentage deviations from the steady state. The inflation target is set to 2%.

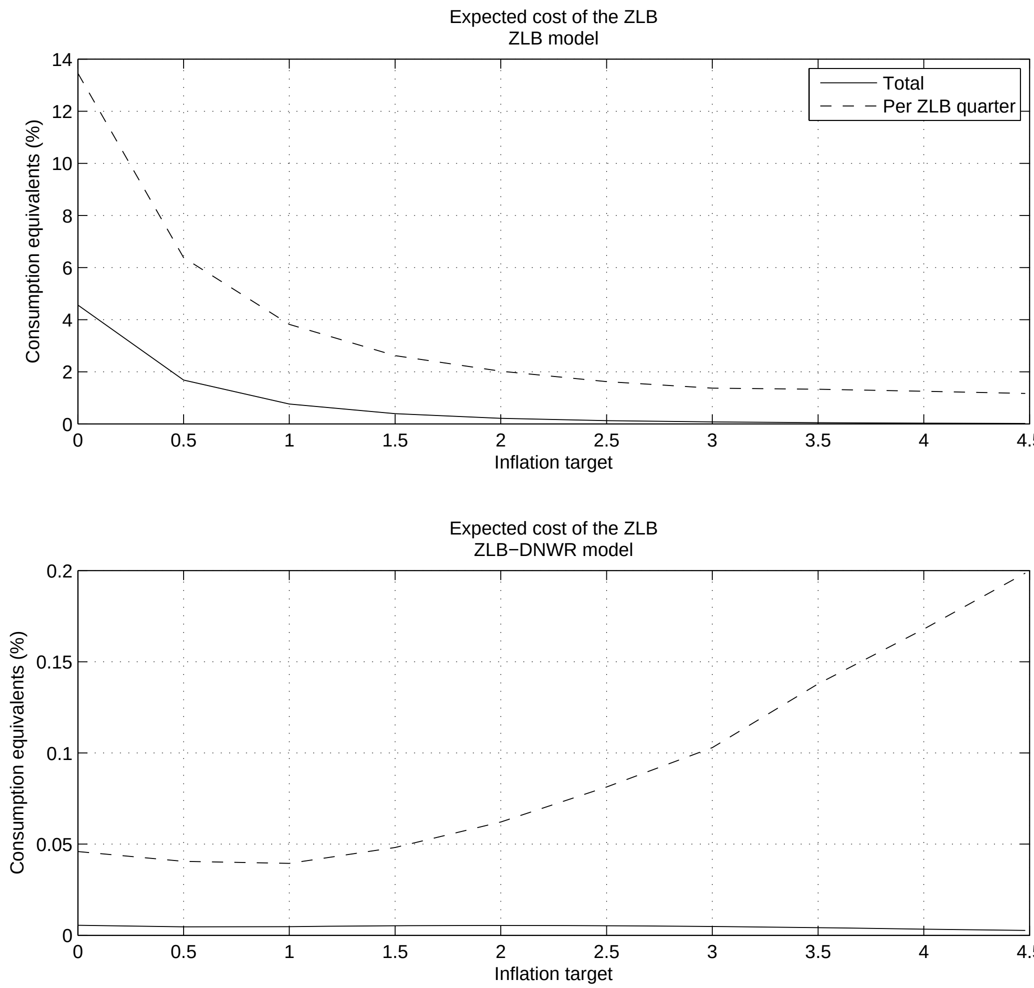

Figure 9: Expected cost of the ZLB as a function of the inflation target in the ZLB (top panel) and in the ZLB-DNWR (bottom panel) models. Solid lines refer to the total expected cost, dashed lines refer to the cost per ZLB quarter. Even when subject to DNWR, wages are assumed to be flexible upwards.

Appendix

A. Private-sector equilibrium

This section states the households and firms' problems, their respective first-order conditions and derives all the equations that define the private-sector equilibrium.

A.1. Households

Each household i faces the following labor demand function of firm j:

$$N_{t,j}^{i}=\left(\frac{W_t^i}{W_t}\right)^{-\eta^w}N_{t,j}, \tag{A.1}$$

which follows from firm j's cost minimization, and, together with definition

$$N_t\equiv\int_0^1 N_{t,j}dj, \tag{A.2}$$

it implies that the total demand for labor type i is

$$N_t^i=\left(\frac{W_t^i}{W_t}\right)^{-\eta^w}N_t. \tag{A.3}$$

Households choose $\left\{C_t^i,N_t^i,D_{t+1}^i,W_t^i\right\}_{t\geq 0}$ to maximize

$$U_0^i=E_0\sum_{t=0}^{\infty}\beta^t\left[\frac{\left(C_t^i\right)^{1-\sigma}-1}{1-\sigma}-\frac{\left(N_t^i\right)^{1+\varphi}}{1+\varphi}\right]Z_t,\quad i\in[0,1], \tag{A.4}$$

subject to

$$D_t^i+(1+\tau_w)W_t^iN_t^i+\Gamma_t-T_t-E_t\left\{Q_{t,t+1}D_{t+1}^i\right\}\geq P_t\left[C_t^i+\Phi_w\left(\Pi_t^{w,i}\right)\right] \tag{A.5}$$

and equation (A.3), given aggregate prices and quantities, initial conditions D_0^i and W_{-1}^i, dividends, Γ_t, and policy. After using equation (A.3) to substitute for N_t^i in equations (A.4) and (A.5), the Lagrangian can be written as

$$\begin{aligned}\mathcal{L}^i=E_0\sum_{t=0}^{\infty}\beta^t\Bigg\{&\left[\frac{\left(C_t^i\right)^{1-\sigma}-1}{1-\sigma}-\frac{\left(N_t\right)^{1+\varphi}}{1+\varphi}\left(\frac{W_t^i}{W_t}\right)^{-\eta^w(1+\varphi)}\right]Z_t\\ &-\Lambda_t^i\Big[P_t\left[C_t^i+\Phi_w\left(\Pi_t^{w,i}\right)\right]+E_t\left\{Q_{t,t+1}D_{t+1}^i\right\}+\\ &-D_t^i-(1+\tau_w)W_t^i\left(\frac{W_t^i}{W_t}\right)^{-\eta^w}N_t-\Gamma_t+T_t\Big]\\ &+\tilde{\Lambda}_t^{w,i}\left[\Pi_t^{w,i}-1\right]\Bigg\},\end{aligned} \tag{A.6}$$

and the corresponding first-order conditions are

$$\left\{C_t^i\right\}: \quad \Upsilon_t \equiv \left(C_t^i\right)^{-\sigma} Z_t = \Lambda_t^i P_t, \tag{A.7}$$

$$\begin{aligned} \left\{W_t^i\right\}: \; & -\frac{\Lambda_t^i P_t \Phi_w'\left(\Pi_t^{w,i}\right)}{W_{t-1}^i} + \beta E_t\left\{\frac{\Lambda_{t+1}^i P_{t+1} W_{t+1}^i \Phi_w'\left(\Pi_{t+1}^{w,i}\right)}{\left(W_t^i\right)^2}\right\} + \\ \Lambda_t^i(1+\tau_w)(1-\eta^w)N_t^i & + \frac{\eta^w \left(N_t^i\right)^{1+\varphi} Z_t}{W_t^i} + \frac{\tilde{\Lambda}_t^{w,i}}{W_{t-1}^i} - \beta E_t\left\{\frac{\tilde{\Lambda}_{t+1}^{w,i} W_{t+1}^i}{\left(W_t^i\right)^2}\right\} = 0, \end{aligned} \tag{A.8}$$

$$\left\{D_{t+1}^i\right\}: \quad -\Lambda_t^i Q_{t,t+1} + \beta \Lambda_{t+1}^i = 0, \tag{A.9}$$

$$\{KT \text{ - conditions}\}: \quad \tilde{\Lambda}_t^{w,i} \geq 0, \;\; \Pi_t^{w,i} \geq 1, \;\; \tilde{\Lambda}_t^{w,i}(\Pi_t^{w,i} - 1) = 0. \tag{A.10}$$

The Euler equation displayed in the main text is obtained by using equation (A.7) to substitute for Λ_t^i in equation (A.9), the fact that $E_t Q_{t,t+1} = R_t^{-1}$ and by imposing symmetry.

To obtain the wage Phillips curve, use equation (A.7) to substitute for Λ_t^i in equation (A.8), which can be rearranged as

$$\begin{aligned} & \eta^w \frac{W_t}{P_t} N_t \left[\frac{(\eta^w - 1)(1+\tau_w)}{\eta^w} - \frac{P_t N_t^{\varphi} C_t^{\sigma}}{W_t}\right] + \Phi_w'\left(\Pi_t^w\right)\Pi_t^w \\ & -\beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\Phi_w'\left(\Pi_{t+1}^w\right)\Pi_{t+1}^w\right\} - \Lambda_t^w + \beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\Lambda_{t+1}^w\right\} = 0, \end{aligned} \tag{A.11}$$

by imposing symmetry, dividing and multiplying both sides of the equation by Υ_t and W_t, respectively, and applying the following definition:

$$\Lambda_t^w \equiv \frac{\tilde{\Lambda}_t^w \Pi_t^w}{\Upsilon_t}. \tag{A.12}$$

Equation (A.11) implies the wage Phillips curve reported in the text. Since $\Lambda_t^w = 0$ if and only if $\tilde{\Lambda}_t^w = 0$, equations (A.10) can be equivalently rewritten as

$$\Lambda_t^w \geq 0, \;\; \Pi_t^w - 1 \geq 0, \;\; \Lambda_t^w(\Pi_t^w - 1) = 0.$$

Finally, it is straightforward to show that the optimal allocation of household i's expenditure implies the following demand for good j:

$$Y_{t,j}^i = \left(\frac{P_{t,j}}{P_t}\right)^{-\eta^p}\left[C_t^i + \Phi_w\left(\Pi_t^{w,i}\right)\right]. \tag{A.13}$$

A.2. Firms

We start by deriving demand and cost functions faced by each firm. The optimal allocation of price-adjustment expenditure across intermediate goods implies that demand of firm z, $z \in [0,1]$, for good j is

$$Y_{t,j,z} = \left(\frac{P_{t,j}}{P_t}\right)^{-\eta^p} \Phi_p\left(\Pi_{t,z}\right). \tag{A.14}$$

Hence, as stated in the text, total demand for good j is

$$\begin{aligned} Y_{t,j} &= \int_0^1 Y_{t,j,z}\, dz + \int_0^1 Y_{t,j}^i\, di = \qquad\qquad (A.15) \\ &= \left(\frac{P_{t,j}}{P_t}\right)^{-\eta^p} Y_t^d; \qquad Y_t^d \equiv C_t + \int_0^1 \Phi_w\left(\Pi_t^{w,i}\right) di + \int_0^1 \Phi_p\left(\Pi_{t,j}\right) dj. \end{aligned}$$

Cost minimization implies real total and marginal cost functions, net of adjustment costs,

$$TC_{t,j} = \int_0^1 W_t^i N_{t,j}^i di = \frac{W_t}{P_t}\left(\frac{Y_{t,j}}{X_t}\right)^{\frac{1}{1-\alpha}}, \tag{A.16}$$

$$MC_{t,j} = \left(\frac{P_{t,j}}{P_t}\right)^{-\frac{\alpha\eta^p}{1-\alpha}} MC_t, \tag{A.17}$$

where the aggregate real marginal cost is defined by

$$MC_t \equiv (\mathcal{M}_t^p)^{-1} \equiv \frac{W_t N_t^\alpha}{P_t(1-\alpha)X_t}, \tag{A.18}$$

so that firm j's profit function can be written as

$$E_0\left\{\sum_{t=0}^{\infty} Q_{0,t}\left[P_{t,j}\left(\frac{P_{t,j}}{P_t}\right)^{-\eta^p} Y_t^d(1+\tau_p) - W_t\left(\frac{P_{t,j}}{P_t}\right)^{-\frac{\eta^p}{1-\alpha}}\left(\frac{Y_{t,j}}{X_t}\right)^{\frac{1}{1-\alpha}} - P_t\Phi_p\left(\Pi_{t,j}\right)\right]\right\},$$

by substituting for $\int_0^1 W_t^i N_{t,j}^i di$ from equation (A.16) into the expression for profits. Its maximization with respect to $P_{t,j}$ yields the following necessary condition:

$$\begin{aligned} &(1-\eta^p)(1+\tau_p)Y_{t,j} + \eta^p \frac{P_t Y_{t,j}}{P_{t,j}} MC_{t,j} + \qquad\qquad (A.19) \\ &-\Phi_p'\left(\Pi_{t,j}\right)\frac{P_t}{P_{t-1,j}} + E_t Q_{t,t+1}\Phi_p'\left(\Pi_{t+1,j}\right)\frac{P_{t+1}P_{t+1,j}}{P_{t,j}^2} = 0. \end{aligned}$$

After using equations (A.9) and (A.7) to substitute for $Q_{t,t+1}$ and Λ_t^i, respectively, and imposing symmetry, the necessary condition becomes

$$\begin{aligned} &(1-\eta^p)(1+\tau_p)Y_t + \eta^p Y_t\left(\mathcal{M}_t^p\right)^{-1} - \Phi_p'\left(\Pi_t\right)\Pi_t + \qquad\qquad (A.20) \\ &\beta E_t\left\{\frac{\Upsilon_{t+1}}{\Upsilon_t}\Phi_p'\left(\Pi_{t+1}\right)\Pi_{t+1}\right\} = 0, \end{aligned}$$

which, after rearranging, gives the price Phillips curve stated in the text.

A.3. Market clearing

The clearing of markets for all goods j, (A.15), and the aggregation function

$$Y_t = \left[\int_0^1 (Y_{t,j})^{\frac{\eta^p - 1}{\eta^p}} \; dj \right]^{\frac{\eta^p}{\eta^p - 1}} \tag{A.21}$$

imply

$$Y_t = Y_t^d = C_t + \int_0^1 \Phi_w \left(\Pi_t^{w,i} \right) di + \int_0^1 \Phi_p \left(\Pi_{t,j} \right) dj. \tag{A.22}$$

By applying symmetry to equation (A.22) and to the production function, one immediately obtains the feasibility constraints stated in the text.

B. Canonical representation

This section derives the natural equilibrium, a first-order approximation of the Phillips curves and a second-order approximation of the utility function about the non-stochastic steady state.

B.1. Natural equilibrium and steady state

The natural equilibrium is easily derived by imposing $\Phi_p = \Phi_w = \Lambda_t^w = 0$ in equations (A.11) and (A.20):

$$\begin{aligned} \frac{P_t N_t^{\varphi} C_t^{\sigma}}{W_t} \mathcal{M}_t^w = 1, \qquad \mathcal{M}_t^w = \frac{\eta^w}{(\eta^w - 1)(1 + \tau_w)}, \\ \frac{W_t N_t^{\alpha}}{(1-\alpha) P_t X_t} \mathcal{M}_t^p = 1, \qquad \mathcal{M}_t^p = \frac{\eta^p}{(\eta^p - 1)(1 + \tau_p)}, \end{aligned} \tag{B.1}$$

which, together with the feasibility constraints, imply that

$$\begin{aligned} N_t^n = \left[\frac{1-\alpha}{\mathcal{M}_t^p \mathcal{M}_t^w} X_t^{1-\sigma} \right]^{\frac{1}{\sigma(1-\alpha)+\varphi+\alpha}}, \quad Y_t^n = \left[\left(\frac{1-\alpha}{\mathcal{M}_t^p \mathcal{M}_t^w} \right)^{1-\alpha} X_t^{1+\varphi} \right]^{\frac{1}{\sigma(1-\alpha)+\varphi+\alpha}}, \\ \frac{W_t^n}{P_t^n} = \left[(\mathcal{M}_t^w)^{\alpha} \left(\frac{1-\alpha}{\mathcal{M}_t^p} \right)^{\sigma(1-\alpha)+\varphi} X_t^{\sigma+\varphi} \right]^{\frac{1}{\sigma(1-\alpha)+\varphi+\alpha}}, \end{aligned} \tag{B.2}$$

where superscript n is used to denote natural equilibrium values. As stated in the text, the natural equilibrium in log-deviations from the non-stochastic steady state is

$$\begin{aligned} n_t^n = \frac{(1-\sigma)\Psi_y}{1+\varphi} x_t, \quad y_t^n = \Psi_y x_t, \quad \omega_t^n = \frac{(\sigma+\varphi)\Psi_y}{1+\varphi}, \\ (\mu_t^p)^n = 0, \quad (\mu_t^w)^n = 0, \quad \Psi_y \equiv \frac{1+\varphi}{\sigma(1-\alpha)+\varphi+\alpha}, \end{aligned} \tag{B.3}$$

after defining $\omega_t^n = log(W_t^n/P_t^n) - log(W/P)$, and steady-state values become

$$N = (1-\alpha)^{\frac{1}{\sigma(1-\alpha)+\varphi+\alpha}}, \quad Y = (1-\alpha)^{\frac{1-\alpha}{\sigma(1-\alpha)+\varphi+\alpha}}, \quad \omega = (1-\alpha)^{\frac{\sigma(1-\alpha)+\varphi}{\sigma(1-\alpha)+\varphi+\alpha}}$$
$$\mathcal{M}^p = 1, \qquad \mathcal{M}^w = 1, \tag{B.4}$$

after substituting for τ_p and τ_w in equation (B.2) from

$$\tau_p = \frac{1}{\eta^p - 1}, \qquad \tau_w = \frac{1}{\eta^w - 1}. \tag{B.5}$$

The assumption that $\Phi_p(\Pi) = \Phi_w(\Pi^w) = 0$ also implies, together with equations (B.4) and (B.1), that

$$Y = C, \tag{B.6}$$
$$\frac{WN}{P} = (1-\alpha)Y. \tag{B.7}$$

B.2. Phillips curves

A first-order approximation of equation (A.11) about the non-stochastic steady state yields

$$\frac{\eta^w WN}{P\mathcal{M}^w}\mu_t^w + \Phi_w''(\Pi^w)^2\pi_t^w - \beta\Phi_w''(\Pi^w)^2\pi_{t+1}^w - \Lambda_t^w + \beta\Lambda_{t+1}^w = 0 \tag{B.8}$$

and

$$\mu_t^w = \omega_t - \left(\sigma + \frac{\varphi}{1-\alpha}\right)y_t + \frac{\varphi}{1-\alpha}x_t, \tag{B.9}$$

where lower-case variables denote log-deviations from the non-stochastic steady state. Equations (B.2) imply that

$$(\mu_t^w)^n = \omega_t^n - \left(\sigma + \frac{\varphi}{1-\alpha}\right)y_t^n + \frac{\varphi}{1-\alpha}x_t = 0, \tag{B.10}$$

so that

$$\mu_t^w = \mu_t^w - (\mu_t^w)^n = \widehat{\omega}_t - \left(\sigma + \frac{\varphi}{1-\alpha}\right)\widehat{y}_t, \tag{B.11}$$

after defining the output gap, $\widehat{y}_t \equiv y_t - y_t^n$, and the real wage gap $\widehat{\omega}_t \equiv \omega_t - \omega_t^n$. Using equation (B.11) to substitute for μ_t^w in equation (B.8) immediately gives the log-linearized wage Phillips curve shown in the text.

A first-order approximation of equation (A.20) about the non-stochastic steady state yields

$$\frac{\eta^p Y}{\mathcal{M}^p}\left(1 - \frac{(\eta^p-1)(1+\tau^p)}{\eta^p}\right)y_t - \frac{\eta^p Y}{\mathcal{M}^p}\mu_t^p - \Phi_p''(\Pi)^2\pi_t + \beta\Phi_p''(\Pi)^2\pi_{t+1} = 0,$$
$$-\eta^p Y\mu_t^p - \Phi_p''(\Pi)^2\pi_t + \beta\Phi_p''(\Pi)^2\pi_{t+1} = 0 \tag{B.12}$$

where the second line follows from equations (B.4) and

$$-\mu_t^p = \omega_t + \frac{\alpha}{1-\alpha} y_t - \frac{1}{1-\alpha} x_t. \tag{B.13}$$

Equation (B.2) implies that

$$-\left(\mu_t^p\right)^n = \omega_t^n + \frac{\alpha}{1-\alpha} y_t^n - \frac{1}{1-\alpha} x_t = 0, \tag{B.14}$$

so that

$$-\mu_t^p = -\mu_t^p + \left(\mu_t^p\right)^n = \widehat{\omega}_t + \frac{\alpha}{1-\alpha} \widehat{y}_t. \tag{B.15}$$

Using equation (B.15) to substitute for μ_t^p in equation (B.12) immediately gives the log-linearized price Phillips curve displayed in the text.

B.3. Welfare function

Let $\mathbb{U}_t$ be the instantaneous utility function. Its second-order approximation about the non-stochastic steady state reads as

$$\begin{aligned} \mathbb{U}_t &= C^{1-\sigma}\left(c_t + \frac{1}{2}c_t^2\right) - \frac{1}{2}\sigma C^{1-\sigma} c_t^2 - N^{1+\varphi}\left(n_t + \frac{1}{2}n_t^2\right) - \frac{1}{2}\varphi N^{1+\varphi} n_t^2 \quad \text{(B.16)} \\ &\quad + \frac{1}{2}\left[C^{1-\sigma} c_t + N^{1+\varphi} n_t\right] z_t + t.i.p. = \\ &= \frac{1}{2}\left[C^{1-\sigma}(1-\sigma)c_t^2 - N^{1+\varphi}(1+\varphi)n_t^2\right] + \left(C^{1-\sigma} c_t - N^{1+\varphi} n_t\right) \\ &\quad + \frac{1}{2}\left(C^{1-\sigma} c_t - N^{1+\varphi} n_t\right) z_t + t.i.p. \end{aligned}$$

We now prove that the last line of equation (B.16) is a third-order term and thereby is zero at a second-order approximation.

First, the production function in its log-linear form,

$$y_t = x_t + (1-\alpha) n_t, \tag{B.17}$$

holds exactly. In addition, a second-order approximation of the resource constraint yields

$$\begin{aligned} & Y\left(y_t + \frac{1}{2}y_t^2\right) = C\left(c_t + \frac{1}{2}c_t^2\right) + \Phi_p' \Pi \pi_t + \Phi_w' \Pi^w \pi_t^w \quad \text{(B.18)} \\ & + \frac{1}{2}\Phi_p'' \Pi^2 \pi_t^2 + \frac{1}{2}\Phi_w'' \left(\Pi^w\right)^2 \left(\pi_t^w\right)^2; \\ & y_t + \frac{1}{2}y_t^2 = c_t + \frac{1}{2}c_t^2 + \frac{1}{2}\frac{\eta^p}{\delta^p}\pi_t^2 + \frac{1}{2}\frac{\eta^w W N}{P\delta^w}\left(\pi_t^w\right)^2; \quad \text{(B.19)} \\ & y_t = c_t + \frac{1}{2}\frac{\eta^p}{\delta^p}\pi_t^2 + \frac{1}{2}\frac{\eta^w(1-\alpha)}{\delta^w}\left(\pi_t^w\right)^2; \quad \text{(B.20)} \end{aligned}$$

where line (B.19) applies definitions

$$\delta^p \equiv \frac{\eta^p Y}{\Phi_p'' \Pi^2} \qquad \delta^w \equiv \frac{\eta^w W N}{P \Phi_w'' \left(\Pi^w\right)^2}, \tag{B.21}$$

and makes use of the steady-state relation (B.6) and of the assumption that $\Phi_p' = \Phi_w' = 0$ at the steady state; line (B.20) follows from the steady-state relation (B.7) and the fact that $y_t^2 = c_t^2$ at a second-order approximation. Finally,

$$\begin{aligned} \left(C^{1-\sigma} c_t - N^{1+\varphi} n_t\right) &= C^{1-\sigma}\left(c_t - \frac{N^{1+\varphi}}{C^{1-\sigma}} n_t\right) \\ &= C^{1-\sigma}\left(c_t - (1-\alpha) n_t\right) = C^{1-\sigma}\left(c_t - y_t\right) \end{aligned} \tag{B.22}$$

is a second-order term because of equation (B.20). Therefore, the last line of equation (B.16) is a third-order term and can be ignored.

Dividing equation (B.16) by $C^{1-\sigma}$ and using equations (B.17) and (B.20) to substitute for c_t and n_t yields

$$\begin{aligned} &\frac{1}{2}\left\{(1-\sigma) y_t^2 - \frac{1+\varphi}{1-\alpha}(y_t - x_t)^2 - \frac{\eta^p}{\delta^p}\pi_t^2 - \frac{\eta^w (1-\alpha)}{\delta^w}\left(\pi_t^w\right)^2\right\} + t.i.p. \\ = \;& -\frac{1}{2}\left\{\left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right)\widehat{y}_t^2 + \frac{\eta^p}{\delta^p}\pi_t^2 + \frac{\eta^w (1-\alpha)}{\delta^w}\left(\pi_t^w\right)^2\right\} + t.i.p., \end{aligned} \tag{B.23}$$

where the second line follows from the fact that $\widehat{y}_t = y_t - y_t^n$, y_t^n is a term independant of policy, and

$$\begin{aligned} &(1-\sigma) y_t^2 - \frac{1+\varphi}{1-\alpha}(y_t - x_t)^2 \\ = \;& \left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right)\left(y_t^2 - 2 y_t y_t^n\right) \\ = \;& \left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right)\widehat{y}_t^2 - \left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right)\left(y_t^n\right)^2. \end{aligned} \tag{B.24}$$

The infinite discounted sum of equation (B.23) coincides with the welfare function, $\mathbb{W}_t$, displayed in the text.

C. Robustness

The robustness of our findings is tested with respect to the distribution of shocks and the parameters of the interest rate rule.

C.1. The inclusion of technology shocks

We first repeat our welfare analysis by including technology shocks (Figures C.1 and C.2). All parameters are calibrated as in Table 1. The cost of the ZLB is magnified in the ZLB model, but it is only marginally affected in the ZLB-DNWR model. Overall, the omission of technology shocks understates our results rather than biasing them upwards. For a two percent inflation target, welfare gains from DNWR range from 0.05 to 0.25 percent of steady-state consumption, depending on the duration of price and wage contracts.

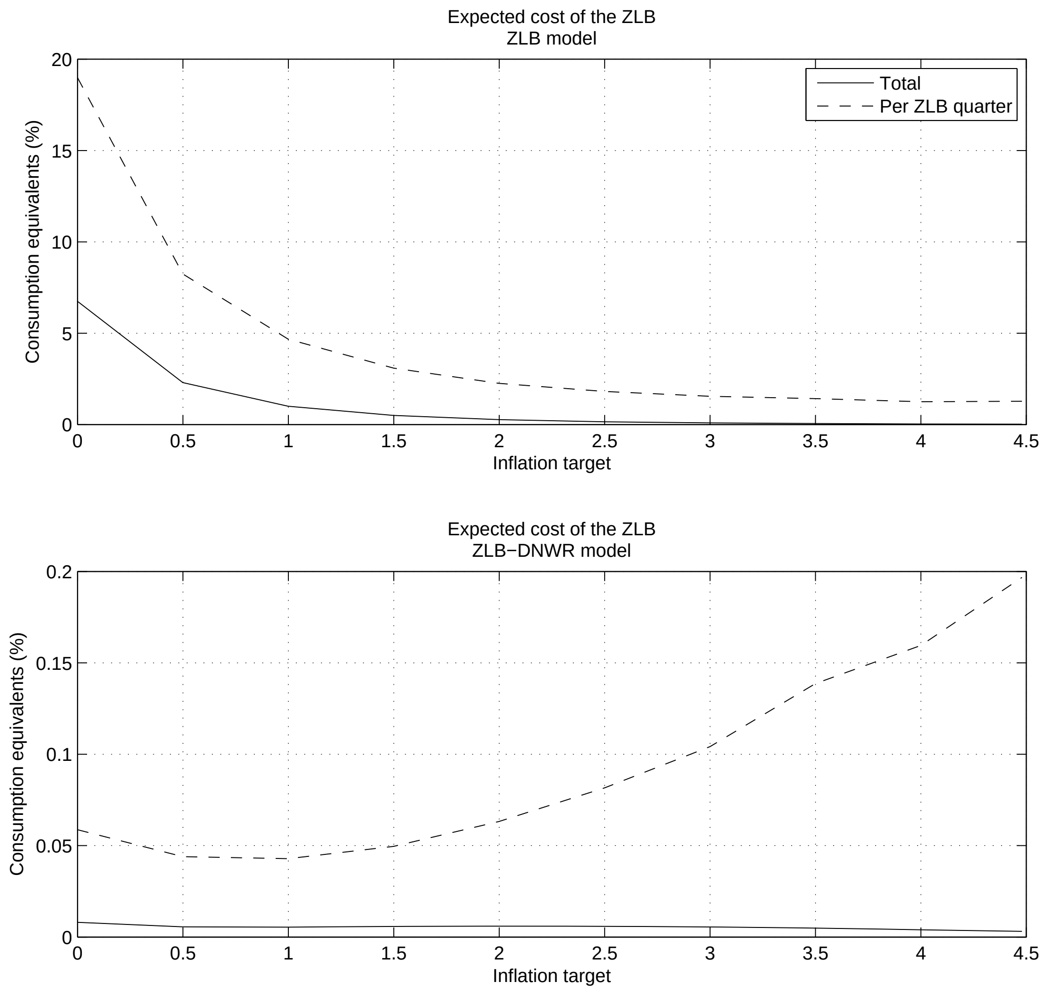

Figure C.1: Expected cost of the ZLB as a function of the inflation target in the ZLB (top panel) and in the ZLB-DNWR (bottom panel) models when technology and preference shocks are both included. Solid lines refer to the total expected cost, dashed lines refer to the cost per ZLB quarter. Even when subject to DNWR, wages are assumed to be flexible upwards.

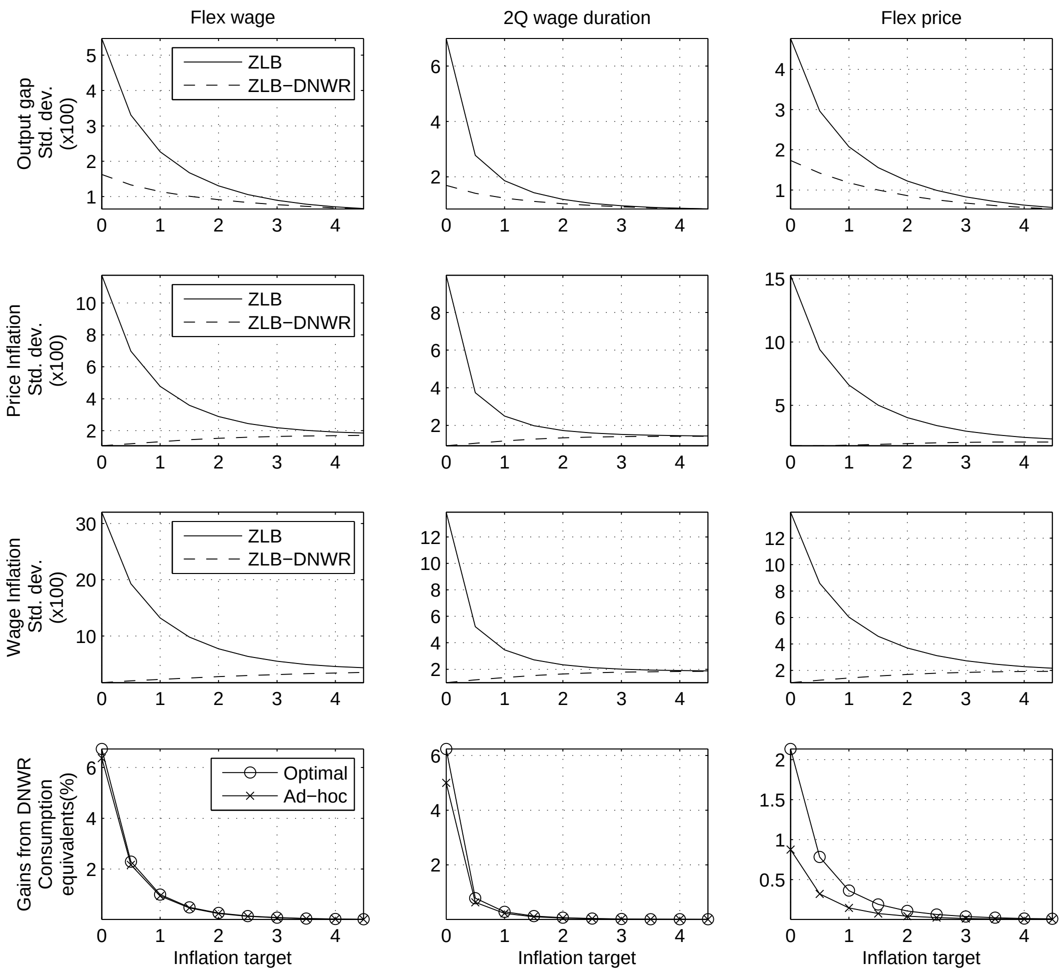

Figure C.2: Standard deviations and welfare in the ZLB (solid lines) and in the ZLB-DNWR (dashed lines) models when technology and preference shocks are both included. Inflation rates are annualized and the output gap is quarterly. Gains from DNWR are computed by subtracting the cost of the ZLB in the ZLB-DNWR model from the cost of the ZLB in the ZLB model. Optimal denotes the cost computed with the micro-founded welfare function. Ad-hoc denotes the cost computed with a loss function that assigns no weight to wage inflation. The flex wage calibration assumes that wages are flexible upwards and a two-quarter price duration. The 2Q wage duration calibration assumes a two-quarter duration for both prices and wages. The flex price calibration assumes flexible prices and a two-quarter wage duration.

C.2. Interest rate rule

The frequency of the ZLB is also affected by the interest rate rule. In particular, it increases with the output weight and falls with the interest rate smoother. We repeat both frequency and welfare analysis for alternative calibrations of the interest rate rule (Figure C.3): results are in the same ballpark of the ones presented in the main text.

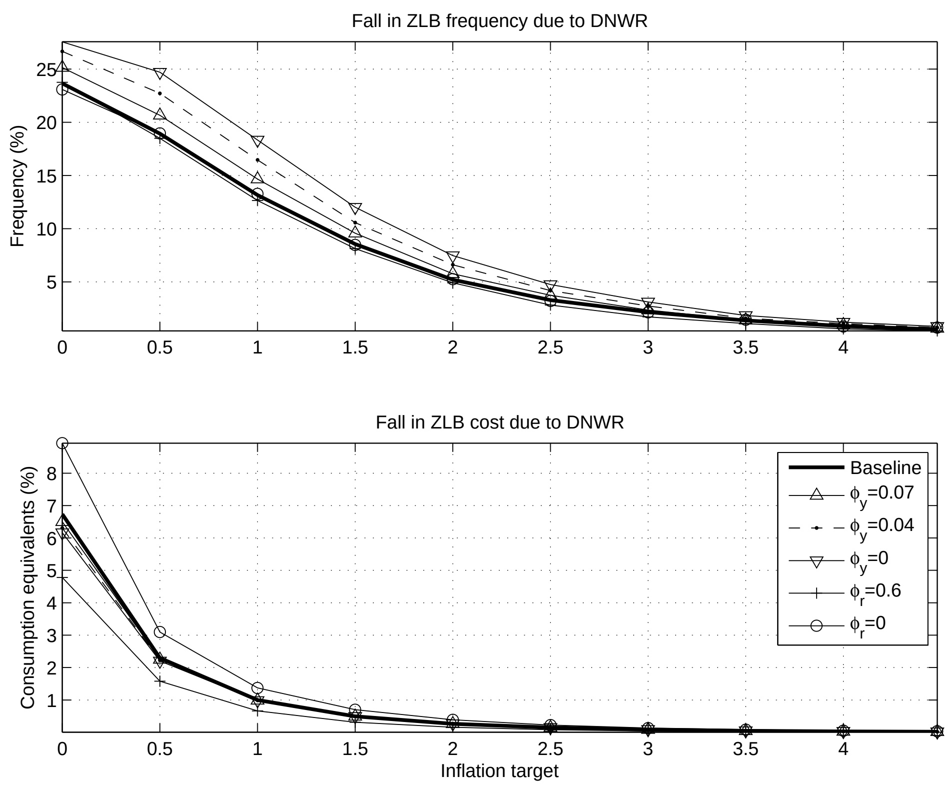

Figure C.3: Fall in ZLB frequency and cost due to DNWR under alternative calibrations of the interest rate rule. Both technology and demand shocks are included; wages are assumed to be flexible upwards.