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How Do Nominal and Real Rigidities Interact?

A Tale of the Second Best

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Abstract

This paper analyses the importance of real wage rigidities, in particular through their interaction with price stickiness, in a calibrated closed-economy New-Keynesian model with monopolistic competition in goods and labour markets, labour and capital as production factors, and staggered nominal price and wage setting. Real wage rigidities result from a combination of staggered wage-setting and partial indexation of non-reset wages to past inflation. Blanchard and Galí (2007) show real rigidities to introduce a trade-off between stabilising inflation and the welfare-relevant output gap. The present paper complements their findings by showing that the welfare costs of real rigidities can be substantial compared to nominal frictions. In a typical "tale of the second-best", we also show that in the presence of real wage rigidities, higher price stickiness can be welfare-enhancing.

Keywords: DSGE model, price stickiness, real wage rigidity, optimal policy

JEL classification: D60, E30

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1. Introduction

The need for DSGE models to feature both nominal and real rigidities in order to be able to fit the data has been acknowledged since at least Christiano *et al.* (2005) and Smets and Wouters (2003), and Blanchard and Galí (2007) showed recently that real rigidities introduce a trade-off between stabilising inflation or the welfare-relevant output gap. The welfare consequences of this monetary policy dilemma have not been explored, however.[1] One interesting question in this regard is whether the magnitude of real rigidities that is likely to be encountered in practice entails significant welfare losses, compared with those from typical degrees of nominal stickiness. Also, the potential importance of real rigidities for monetary policy raises the question of whether and how they interact with nominal frictions in terms of their impact on welfare.

This paper addresses these issues through a closed-economy New-Keynesian model with monopolistic competition in goods and labour markets, labour and capital as production factors, forward-looking agents and staggered nominal price and wage setting. We focus on one major type of real rigidity, namely real wage rigidity, which is modelled as resulting from a combination of staggered wage-setting and partial indexation of non-reset wages to past inflation. The benchmark calibration of our simple model captures most of the key features of quarterly macroeconomic data for the United States.

Regarding monetary policy, with the exception of the benchmark calibration of the model which relies on a simple interest rule, we assume the central bank to implement the optimal Ramsey solution, *i.e.* the optimal commitment strategy for given exogenous shock and economic structure. The optimal commitment achieves the best possible stabilisation result and constitutes the policy loss frontier. This assumption also allows a clearer focus on the welfare losses from various types of real and nominal rigidities and the interactions between them. Indeed under the alternative policy framework of simple interest rate rules, the policy rule might itself affect the welfare losses from, and the interaction between nominal and real rigidities.

The main findings from the paper are two-fold. First, under the technology and price mark-up shocks considered here, real wage rigidity implies substantial welfare losses, much larger in fact than those from nominal rigidities. Second, for any given degree of real wage rigidity, welfare losses *decrease* in the degree of nominal price rigidity for high but still plausible values of the latter. This is because nominal frictions dampen the initial price and wage reactions to exogenous shocks and the magnitude of second-round effects. The result suggests that stronger price rigidity can be second best under real wage inertia. By contrast, reducing real wage inertia is welfare-enhancing whatever the degree of nominal price stickiness.

The remainder of this paper proceeds as follows. Section 2 outlines the New-Keynesian framework and briefly sketches the notion of optimal Ramsey policy. Section 3 discusses the scenarios to be simulated and the parameter calibration. Section 4 presents and discusses the numerical results, while Section 5 performs selected robustness checks. Section 6 summarises the main findings and concludes.

2. The model

The analysis builds on a closed-economy DSGE model with monopolistic competition in goods and labour markets, labour and capital as production factors, forward-looking agents and staggered nominal price and wage setting. In each period, the share of wage contracts that is not re-optimised is partially indexed to past inflation as in *e.g.* Fernández-Villaverde *et al.* (2010), Gertler *et al.* (2008) and Smets and Wouters (2003). The combination of staggered nominal wage setting and partial wage indexation creates real wage rigidity in the labour market. This explicit modelling of real wage rigidity alleviates the use of more *ad hoc* short-cuts used in some recent papers, such as *e.g.* Blanchard and Galí (2007) or Ascari and Merkl (2009). Motivating real wage rigidity is warranted given its crucial role in the welfare analyses carried out in this paper, and using a shortcut instead would appear doubtful in this context. Overall, the model is very similar to that of Canzoneri *et al.* (2007), except that ours features both nominal and real wage rigidities and optimal

[1] An early paper by Gray (1978) explored the desirability of real rigidities under nominal and real shocks. However, while Gray (1978) considered a rather *ad hoc* loss function, we look explicitly at social welfare and perform an extensive welfare analysis of the interactions between real and nominal rigidities.

monetary policy, rather than only nominal wage rigidities and estimated simple interest rules. The model is also similar in spirit, although less complex than Smets and Wouters (2003).

2.1 Firms

The economy is home to a continuum of firms indexed by *f* on a unit interval. Each firm combines the capital stock $K_{f,t-1}$ that is available at the beginning of each period with the contemporaneous bundle of labour $N_{f,t}$ (defined in equation (15) below) to produce a firm-specific differentiated good using the Cobb-Douglas production function:

(1) $$Y_{f,t} = e^{a_t} K_{f,t-1}^{\alpha} N_{f,t}^{1-\alpha}$$

where $0 \leq \alpha \leq 1$. Total factor productivity is assumed to be equal across firms and subject to technology shocks:

(2) $$a_t = \rho^a a_{t-1} + \nu_t^a$$

Firms choose the cost-minimising combination of factor inputs. The cost-minimising factor mix depends on factor prices, *i.e.* on wages W_t and capital costs R_t, and the marginal factor returns:

(3) $$K_{f,t-1} / N_{f,t} = \alpha / \left(1-\alpha\right)\left(W_t / R_t\right).$$

The steady-state relationship between firm-level output and employment under cost-minimising production is:

$$Y_{f,t} = e^{a_t} \left[\alpha / \left(1-\alpha\right) W_t / R_t\right]^{\alpha} N_{f,t}.$$

The cost-minimising firm's real marginal cost of producing output is:

(4) $$MC_{f,t} = 1 / \left[\alpha^{\alpha} \left(1-\alpha\right)^{1-\alpha} e^{a_t}\right] R_t^{\alpha} W_t^{1-\alpha} / P_t.$$

Household preferences for the firm sector's differentiated output are identical for both consumer and capital goods and given by the CES aggregate:

$$Y_t = \left[\int_0^1 Y_{f,t}^{(\eta-1)/\eta} df \right]^{\eta/(\eta-1)}$$

with η>1 being the elasticity of substitution between different output varieties. The demand for an individual variety f of price $P_{f,t}$ is:

(5) $$Y_{f,t} = \left(P_{f,t} / P_t \right)^{-\eta} Y_t .$$

The price P_t of the composite good, which is also the aggregate price level, follows as:

$$P_t = \left[\int_0^1 P_{f,t}^{1-\eta} df \right]^{1/(1-\eta)} .$$

Empirical research has provided ample evidence for the practical relevance of nominal price stickiness (*e.g.* Bils and Klenow 2004). Producers reset prices infrequently in response to new information. Potential explanations for sluggish adjustment include adjustment costs and contractual obligations. Following Calvo (1983), this paper assumes firms to adopt staggered price setting, *i.e.* firms set prices in staggered contracts of random duration. In any period, each firm re-optimises its price contract with probability 1-γ, and maintains the old price with probability γ.

Infrequent contract adjustment makes price setting a dynamic optimisation problem. The re-optimising firm sets the new price $P_{f,t}^*$ to maximise the present value of profits over the expected contract duration:

(6) $$E_t \sum_{i=0}^{\infty} (\gamma\beta)^i \lambda_{t+i} P_{t+i} \left(P_{f,t}^* / P_{t+i} Y_{f,t+i} - MC_{f,t+i} \right),$$

where β and λ_t are the households' discount factor and the marginal utility of household wealth defined below in equation (21). Maximising profits (6) subject to the demand function (5) yields:

(7) $$P_{f,t}^* = e^{\varepsilon_t^p} \eta / (\eta - 1) \left[E_t \sum_{i=0}^{\infty} (\gamma\beta)^i \lambda_{t+i} P_{t+i}^{1+\eta} MC_{f,t+i} Y_{t+i} \right] / \left[E_t \sum_{i=0}^{\infty} (\gamma\beta)^i \lambda_{t+i} P_{t+i}^{\eta} Y_{t+i} \right]$$

where we add the variable:

(8) $$\varepsilon_t^p = \rho^p \varepsilon_{t-1}^p + \nu_t^p$$

as an exogenous price mark-up shock.[2] As all producers face identical constraints, the optimal price is identical across all firms, so that $P_{f,t}^{*}=P_{t}^{*}$.

The law of large numbers implies that the share of firms that resets price contracts in a given period equals the probability of price adjustment 1-γ, whereas γ indicates the degree of nominal price stickiness. The dynamics of the aggregate price level follows as:

(9) $$P_t = \left[\gamma P_{t-1}^{1-\eta} + (1-\gamma)\left(P_t^*\right)^{1-\eta} \right]^{1/(1-\eta)}.$$

Combining firm-level production (1) and the demand function (5) gives aggregate output:

(10) $$Y_t \int_0^1 \left(P_{f,t} / P_t \right)^{-\eta} df = e^{a_t} K_{t-1}^{\alpha} N_t^{1-\alpha}$$

where $K_{t-1} = \int_0^1 K_{f,t-1} df$ is the aggregate available capital stock and $N_t = \int_0^1 N_{f,t} df$ is total employment. The expression $D_t^P \equiv \int_0^1 \left(P_{f,t} / P_t \right)^{-\eta} df$ in equation (10) measures the dispersion of prices across firms. Canzoneri *et al.* (2007) show that this price dispersion evolves as:

(11) $$D_t^P = (1-\gamma)\left(P_{f,t} / P_t \right)^{-\eta} + \gamma \left(P_{t-1} / P_t \right)^{-\eta} D_{t-1}^P .$$

Price dispersion between goods leads to inefficient household choices. Relative demand in the flexible economy depends on the utility of variety f and the resource costs of its production, which here are both assumed to be identical across all varieties. The marginal utility of consuming variety f is decreasing with the level of its consumption. Price stickiness, i.e. γ>0, that implies different prices for goods with identical utility and resource costs distorts the demand decisions made by optimising households.

[2] Monopolistic competition implies an inefficiently low production level as prices are set with a mark-up above the marginal production costs. The size of the distortion varies inversely with the elasticity of substitution η and is therefore a positive function of market power. Many models introduce a production or employment subsidy financed by lump-sum taxes to correct the steady-state distortion, so that steady-state production would equal the efficient output under perfect competition. Because such corrective subsidy financed by non-distortionary taxes has little practical relevance, we follow Benigno and Woodford (2005) and do not consider it throughout this paper.

2.2 Households

The economy is populated by a continuum of households indexed by h on a unit interval. Households consume goods $C_{h,t}$, invest in capital goods $I_{h,t}$ and lend them to firms, and supply a differentiated labour service $N_{h,t}$ to all firms. Each individual household maximises welfare, which is the discounted stream of expected period utility over an infinite planning horizon:

(12) $$E_t \sum_{i=t}^{\infty} \beta^i \left[\ln\left(C_{h,t+i} - H_{h,t+i}\right) - \kappa / \left(1+\varphi\right) N_{h,t+i}^{1+\varphi} \right].$$

The variable $H_t \equiv \chi C_{h,t-1}$ allows for habit persistence in the level of consumption when $0<\chi\leq 1$. Such habit persistence is ignored in our benchmark calibrated model (*i.e.* $\chi=0$, see Section 3 below), but it is considered in Section 5 among a range of robustness checks for our main results. Parameters κ and φ indicate the relative weight of leisure in the utility function and the inverse of the elasticity of labour supply, respectively.

Household h faces the nominal period budget constraint:

(13) $$W_{h,t} N_{h,t} + B_{h,t} + R_{h,t} K_{h,t-1} + D_{h,t} = P_t \left(C_{h,t} + I_{h,t}\right) + B_{h,t+1} / \left(1 + i_t\right).$$

The income side features the wage $W_{h,t}$ paid by firms for the labour service $N_{h,t}$, the return $B_{h,t}$ on a safe asset in zero net supply, the return $R_{h,t}$ on capital $K_{h,t-1}$ lent to firms, and firm profits that are distributed as dividends $D_{h,t}$. The expenditure side combines the purchases of the composite consumption and capital goods and purchases of the safe asset that pays a return of $B_{h,t+1}$ in the subsequent period. The current price of the safe asset is $B_{h,t+1}/(1+ i_t)$, where i_t is the nominal interest rate.

The capital stock is subject to depreciation at rate δ and quadratic adjustment costs ψ, and evolves as:

(14) $$K_{h,t} = \left(1-\delta\right) K_{h,t-1} + I_{h,t} - \psi / 2 \left(I_{h,t} / K_{h,t-1} - \delta\right)^2 K_{h,t-1}.$$

The aggregate labour service N is a CES aggregate of the individual households' labour services:

(15) $$N_t = \left[\int_0^1 N_{h,t}^{(\theta-1)/\theta} dh \right]^{\theta/(\theta-1)}$$

with $\theta>1$ as the elasticity of substitution between the labour services h. The demand for the individual labour service h given its price $W_{h,t}$ is:

(16) $$N_{h,t} = \left(W_{h,t} / W_t\right)^{-\theta} N_t .$$

The price of the composite labour service, which is the aggregate wage, follows as:

$$W_t = \left[\int_0^1 W_{h,t}^{1-\theta} dh\right]^{1/(1-\theta)} .$$

Similarly to Calvo pricing, households set wages in staggered wage contracts with a re-optimisation probability of 1-ω in each period; ω is the probability that the old contract remains in effect. Those wages that are not re-optimised in a given period, *i.e.* the surviving wage contracts, are indexed to past inflation with the indexation scheme:

(17) $$x_t \equiv \left(P_{t-1} / P_{t-2}\right)^{\sigma} .$$

where parameter $0<\sigma<1$ indicates the strength of indexation. This modelling of wage indexation is similar to *e.g.* Fernández-Villaverde et al. (2010), Gertler et al. (2008) and Smets and Wouters (2003). The indexation of surviving wage contracts to inflation is a source of real wage rigidity, which for a given σ is stronger the higher the probability ω that the old contract remains in effect.

Infrequent contract adjustment makes wage setting a dynamic optimisation problem. The re-optimising household sets the new wage $W_{h,t}^*$ to minimise the disutility of work over the expected contract duration and given the marginal utility of labour income and the labour demand function of firms. Taking the first-order condition for $W_{h,t}^*$ from maximising individual welfare (12) under the constraints (13) and (16) and the indexation scheme (17), and rearranging the expression yields:

(18) $$W_t^{*1+\phi\varphi} = \kappa \frac{\theta}{\theta-1} \frac{E_t \sum_{i=0}^{\infty} (\omega\beta)^i \left(W_{t+i} / \prod_{s=1}^{i} x_{t+s}\right)^{\theta(1+\varphi)} N_{t+i}^{1+\varphi}}{E_t \sum_{i=0}^{\infty} (\omega\beta)^i \lambda_{t+i} \left(\prod_{s=1}^{i} x_{t+s}\right)^{1-\theta} W_{t+i}^{\theta} N_{t+i}} .$$

With all households facing an identical utility function and identical constraints, the optimal wage is identical across all households, *i.e.* $W_{h,t}^{*}=W_{t}^{*}$.[3]

The law of large numbers implies that the share of re-optimising households in a given period equals the probability of wage re-optimisation 1-ω, whereas a share ω of household indexes (partially or fully) past wages to past inflation. The aggregate wage level evolves as:

(19) $$W_t = \left[\omega \left(x_t W_{t-1} \right)^{1-\theta} + \left(1-\omega\right) W_t^{*1-\theta} \right]^{1/(1-\theta)}.$$

Wage stickiness, *i.e.* ω>0, implies that wages are not identical across all households h if the economy is away from its steady state. Given the demand function (16), labour demand of firms and work effort will differ across households. The opportunity for households to insure against idiosyncratic labour and capital income risks in a complete contingent claims market makes households identical in terms of the consumption and investment decisions, however. The households' first-order conditions for consumption and investment from maximising welfare (12) under the budget constraint (13) and the law of motion of the capital stock (14) can therefore be aggregated to:

(20) $$P_t \lambda_t = 1/\left(C_t - \chi C_{t-1}\right) - \beta\chi / E_t\left(C_{t+1} - \chi C_t\right)$$

(21) $$\lambda_t = \beta\left(1+i_t\right) E_t \lambda_{t+1}$$

(22) $$P_t \lambda_t = \xi_t - \xi_t \psi\left(I_t / K_{t-1} - \delta\right)$$

(23) $$\xi_t = \beta E_t\left(\lambda_{t+1} R_{t+1} + \xi_{t+1}\left[1-\delta-\psi/2\left(I_{t+1}/K_t-\delta\right)^2 + \psi\left(I_{t+1}/K_t-\delta\right) I_{t+1}/K_t\right]\right).$$

Market clearing for productive capital implies and requires $\int_0^1 K_{h,t}dh = \int_0^1 K_{f,t}df$, market clearing for labour services $\int_0^1 N_{h,t}dh = \int_0^1 N_{f,t}df$ and market clearing for total output $Y_t = C_t + I_t$.

[3] The wage mark-up under monopolistic competition implies lower equilibrium employment than in the undistorted economy as the real wage lies above the marginal rate of substitution between leisure and consumption. The size of the distortion varies inversely with the elasticity of substitution θ and is therefore a positive function of the market power. As for the price mark-up in equation (7), we exclude a corrective wage subsidy financed by non-distortionary taxes as an unrealistic scheme.

2.3 Monetary policy

The paper investigates the stabilising potential of optimal Ramsey policy as the optimal commitment solution for alternative combinations of nominal price and real wage rigidity. The monetary authority maximises conditional expected social welfare subject to the household and firm sectors' behavioural equations and the market-clearing conditions of the economy that constitute the policy maker's constraints (Khan *et al.,* 2003; Levin *et al.,* 2006). The policy maker's first-order conditions replace standard instrument rules in this setup.

Following Canzoneri *et al.* (2007), we define social welfare as:

(24) $$E_t \sum_{i=t}^{\infty} \beta^i \left[\ln\left(C_{t+i} - H_{t+i}\right) - \kappa / \left(1+\varphi\right) \int_0^1 N_{h,t+i}^{1+\varphi} dh \right],$$

with $C_t - H_t = \int_0^1 \left(C_{h,t} - H_{h,t}\right) dh = C_{h,t} - H_{h,t}$ being average consumption adjusted for consumption habits and $-\kappa / \left(1+\varphi\right) \int_0^1 N_{h,t}^{1+\varphi} dh$ being the average disutility of work (note again that consumption habits are ignored in our benchmark specification but are considered as part of a sensitivity analysis in Section 5).

If wages are flexible, *i.e.* ω=0, then $W_{h,t}$=W_t, so that given the labour demand equation (14) firms hire the same amount of labour services from each household and the average equals the individual disutility of work $\int_0^1 N_{h,t}^{1+\varphi} dh = N_{h,t}^{1+\varphi}$. In this special case of identical demand for all labour services h, social welfare (24) boils down to the individual welfare function (12). If wages are sticky, *i.e.* ω>0, and the economy is outside its steady state, wage dispersion makes firms hire different amounts of labour services from different households. Given the increasing marginal disutility of working effort in equation (12) and the decreasing marginal contribution of labour services h in the composite labour service, the disutility will not be minimised and the composite labour service not be maximised for the given and dispersed aggregate labour input $\int_0^1 N_{h,t} dh$. Canzoneri *et al.* (2007) show the average disutility of labour effort to be:

(25) $$\int_0^1 N_{h,t}^{1+\varphi} dh = N_t^{1+\varphi} \int_0^1 \left(W_{h,t} / W_t\right)^{-\theta(1+\varphi)} dh$$

The evolution of wage dispersion $D_t^W \equiv \int_0^1 \left(W_{h,t} / W_t \right)^{-\theta(1+\varphi)} dh$ with staggered wage setting and wage indexation follows as:

(26) $$D_t^W = (1-\omega)\left(W_t^* / W_t \right)^{-\theta(1+\varphi)} + \omega\left(x_t W_{t-1} / W_t \right)^{-\theta(1+\varphi)} D_{t-1}^W .$$

The Ramsey optimal policy implements the best stabilisation outcome for a given economic structure and given exogenous shocks. Simulating the shocks under optimal policy yields the loss frontier, *i.e.* the smallest possible welfare loss, for alternative values of nominal and real rigidity. The optimal commitment solution therefore constitutes an important benchmark to assess the welfare costs and policy implications of nominal and real rigidities. We use the algorithm of Levin *et al.* (2006) to derive the optimal commitment solution in Dynare. In order to check robustness of the interaction results, we also briefly assess the welfare loss under a simple interest rate rule that may provide a better approximation to the actual conduct of monetary policy, and also look at alternative model specifications without capital adjustment costs and/or with habit persistence in consumption.

3. Simulation scenarios and benchmark calibration

This paper studies the welfare costs from, and the interactions between nominal price and real wage rigidities under optimal monetary commitment, *i.e.* under the optimal stabilisation of the exogenous shock given the structural frictions and inefficiencies. We perform this welfare analysis by varying the wage and price rigidity parameters of our model around their benchmark values. The calculation of first and second moments of the variables and the welfare comparison are all based on first-order and second-order approximations of the model undertaken in Dynare 4.

Table 1 specifies the parameters used in our benchmark calibration. The structure of our model is very similar to that of Canzoneri *et al.* (2007), whose parameter values were shown to match most variances and covariances in U.S quarterly macroeconomic data. Therefore we use their parameter values, which, looking at the literature, also turn out to be fairly consensual values. One exception is the wage indexation parameter, which is specific to our model and the main source – in combination with nominal wage stickiness – of real wage rigidity. We set this parameter equal to 0.7, which corresponds roughly to the average of estimates for the United States across the papers by Gertler *et al.* (2008), Smets and Wouters (2003), Sahuc and Smets (2008) and Fernández-Villaverde *et al.* (2010).[4] Since we explore optimal monetary policy, we do not need to calibrate a monetary policy rule, unlike Canzoneri *et al.* (2007). However, insofar as the simple monetary policy rule estimated and used in Canzoneri *et al.* (2007) influenced the choice of their other model parameters, the calibration of our own model implicitly relies on that simple monetary policy rule – as should be the case for the model to match key features of U.S. data.

Our welfare analysis focuses essentially on productivity shocks, although we illustrate the generality of our findings by considering price mark-up shocks in some simulation exercises. The standard deviation of productivity shocks and the persistence parameter are set equal to 0.01 and 0.9, respectively, close to the average values considered in Canzoneri *et al.* (2007). While these parameter choices matter for the benchmark calibration of the model, they do not make a major difference for our subsequent welfare analysis, which focuses on the *relative* costs of real and nominal rigidities and how they interact. Similar persistence and volatility parameters are used for illustrative purposes in the price mark-up shock simulations.

[Table 1 here]

Since our model differs slightly from that of Canzoneri *et al.* (2007) in that it features wage indexation and does not distinguish between private and public consumption, using their parameter values does not strictly guarantee that our benchmark calibration matches key moments in the data. Therefore in Table 2 we check whether our calibrated model is indeed able to capture key volatilities, correlations and auto-correlations in quarterly U.S macroeconomic data. For the sake of consistency, the analysis is based

[4] We do the same for the choice of the consumption habit persistence coefficient in the robustness checks performed in Section 5 below. However, that coefficient is set equal to zero in the benchmark model and the welfare analysis of Section 4, consistent with a calibration strategy based on parameter values used in Canzoneri *et al.* (2007) who ignore habit persistence.

on both the technology shocks as calibrated above and on the monetary policy rate shocks considered in Canzoneri *et al.* (2007).[5] The model's variables are expressed as log deviations from a deterministic steady state, and moments are calculated from a linear approximation. Both the model data and the actual data are in logarithms and Hodrick-Prescott filtered with parameter λ=1600. Our simple model comes fairly close to matching the volatility of output in U.S historical data, as well as the volatilities and correlations with output of consumption, investment and employment.[6] The model also captures the negative correlation between inflation and output, but it tends to overstate its strength and to understate inflation volatility relative to the volatility of output. The same holds for real wages, which tend to be more volatile and less strongly correlated with output than the model predicts. This limited match for real wages is similar to the calibration results in Canzoneri *et al.* (2007). The limited match for real wages seems to be due primarily to the omission in this extremely simple model of a whole range of shocks that reduce the correlation between real wages and output.[7] The limited match is not indicative for an overemphasis on wage indexation and stickiness in the model. Using survey data, Barattieri *et al.* (2010) estimate wage indexation and contract duration parameters that are similar in size to those of Table 1. The time-varying estimates by Fernández-Villaverde and Rubio-Ramírez (2007) suggest that the indexation parameter has even increased to higher values in recent decades. Varying the wage indexation and Calvo wage stickiness parameters within plausible parameter ranges does furthermore not significantly affect the correlation between real wages and output under the given set of exogenous shocks in Table 2.

[5] Canzoneri *et al.* (2007) also consider government spending shocks, which are ignored here as we do not distinguish between private and public consumption. Making this distinction would be straightforward, but it was not found to be crucial in practice in the context of this paper since our simple calibrated model is able to capture most of the key features of U.S. quarterly macroeconomic data reasonably well.

[6] The high correlation in the model between consumption and output is linked to the closed-economy framework in which domestic demand and output evolve in line in each period, a constraint that does not exist in the actual data.

[7] Candidate shocks include fiscal policy. However, the degree to which fiscal shocks improve the match depends on the degree of substitutability between private and public expenditure, which is difficult to calibrate. Canzoneri *et al.* (2007) assume purely wasteful government spending. Increases in wasteful spending reduce household wealth, which leads to a positive response of labour supply. The effect reduces the positive correlation between output and real wages and improves the fit with actual data in their model.

[Table 2 here]

4. Results

We now analyse the effects of real wage rigidity and its interaction with price stickiness within the calibrated model under technology shocks and optimal monetary policy commitment. We start by looking at the behaviour of the economy for a few selected degrees of nominal and real rigidities before turning to welfare analysis and generalising the results. Table 3 reports the first and second moments for log output, the output gap,[8] inflation and the nominal interest rate for three combinations of nominal and real rigidities: i) the benchmark values of nominal price stickiness, nominal wage stickiness and wage indexation; ii) a lower degree of wage indexation, corresponding to lower real wage rigidity, iii) a higher degree of price stickiness.[9]

[Table 3 here]

Comparing weaker wage indexation with the benchmark calibration, the volatility of log output, the output gap, inflation and the nominal interest rate are found to be lower under weaker wage indexation and thereby under lower real wage rigidity. By contrast, volatilities appear to be *lower* when price stickiness is higher. The impulse responses in Figure 1 further illustrate the findings from Table 3 on macroeconomic volatility under different degrees of nominal and real rigidities. This chart plots log output, the output gap, inflation and the nominal interest rate, but also the real interest rates, log consumption, log investment, log employment and the log real wage, in deviations from steady-state levels. Compared with the

[8] Blanchard and Galí (2007) refer to this variable as the *welfare-relevant* output gap. It measures the log difference between actual output and production under fully flexible prices and wages. Thus, the latter measure of potential production displays the optimal unconstrained behaviour of household and firms in reaction to the exogenous shock.

benchmark calibration, more flexible real wages mitigate the response of inflation and the output gap and speed up the adjustment to a technology shock. Likewise, *stronger* price inertia dampens the amplitude of the inflation and output gap responses.

Table 3 and Figure 1 suggest an important role for the nominal-real rigidity interaction in shaping the interest rate, inflation and output gap responses to technology shocks, and to macroeconomic shocks more broadly. Instead of reinforcing the effect of real wage persistence, sticky prices dampen the inflation and output response to shocks, for a given level of real rigidity. Flexible prices amplify the initial inflation response to the negative technology shock considered in Figure 1. In a context where real wages respond little to the decline in output and labour demand, higher initial inflation pushes up the nominal wage, thereby reinforcing inflationary pressures. The monetary authority concerned about inflation and the associated inefficiency reacts more strongly and engineers a larger output contraction. By contrast, higher nominal price rigidity dampens initial inflationary pressures and improves both inflation and output stabilisation, for a given degree of real rigidity. In other words, when real wage rigidities are present in the economy, price stickiness dampens the initial goods price response to negative technology shocks and mitigates the second-round effect from nominal wages on production costs. A symmetric line of reasoning holds for positive technology shocks.

[Figures 1 here]

Turning now to welfare analysis, Figure 2 plots the welfare loss relative to the fully flexible economy (expressed as a percentage of steady-state consumption) across the parameter space γ=0.1-0.9 and σ=0-1, *i.e.* for a broad range of degrees of price stickiness and real wage rigidity, with grid intervals of

[9] Standard deviations in Table 3 are Hodrick-Prescott filtered with parameter λ=1600. Considering raw standard deviations would yield larger values, but it would not change the ranking of standard deviations across different combinations of rigidity parameters, which is the main focus of Table 3.

0.1.[10] Two main findings stand out. First, regardless of the degree of price stickiness, the loss strongly increases in the degree of real wage rigidity. Second and most interestingly, for high but still plausible degrees of real wage rigidity (including the benchmark value), higher price stickiness reduces the welfare loss, reflecting the aforementioned interaction. In other words, stronger nominal rigidity can be second best in the presence of real rigidities.

[Figures 2 here]

Another important conclusion from Figure 2 is that the welfare cost of real wage rigidity is significantly larger than that from price stickiness. This can further be seen in Figure 3, which looks at the welfare costs of extreme values of real wage rigidity by iterating on *both* the nominal wage persistence and wage indexation parameters. Figure 3 shows that when price stickiness is at its benchmark value, extreme values of both wage persistence and wage indexation parameters – corresponding to extreme values of real wage rigidity – can yield welfare losses as high as ½ % of steady-state consumption relative to a fully flexible economy. This is much higher than the welfare losses from strong price stickiness in Figure 2. For instance, when the nominal wage persistence and wage indexation parameters – and thereby the degree of real rigidity – are set equal to their benchmark values ($\omega = 0.75$ and $\sigma = 0.7$), the welfare losses from extreme values of price stickiness never exceed 0.1% to 0.15% of steady-state consumption.

[Figures 3 here]

[10] The nominal wage stickiness parameter ω is set constant and equal to its benchmark value across all the simulations run to produce Figure 2. Since real wage rigidity in our model results from a combination of nominal wage stickiness and wage indexation, we can vary the degree of real wage rigidity by varying either nominal wage stickiness or wage indexation relative to their benchmark values (or both). Figure 2 is based on the latter approach, but the former – not shown here – brings qualitatively similar results.

5. Robustness checks

We illustrate the robustness of our main results by performing three simple sensitivity exercises in which alternative shocks, model specifications and monetary policy assumptions are considered. First, performing the welfare analysis for price mark-up rather than technology shocks yields comparable relative losses from, and a similar interaction between nominal and real rigidities (Figure 4).[11] Second, considering a model without capital adjustment costs, *i.e.* a model without any real friction other than real wage rigidity, does not significantly alter the shape of the welfare loss surface either (Figure 5). Likewise, a version of the model featuring habit persistence in consumption yields similar results (Figure 6). Finally, our main findings are robust to, and are in fact even strengthened under an alternative monetary policy assumption where the central bank implements a simple rule rather than optimal policy. Under the simple interest rate rule estimated by Canzoneri *et al.* (2007) on U.S. data, which was mentioned in Section 3, the relative welfare costs of real and nominal rigidities are roughly unchanged, while greater price stickiness is now *always* welfare-enhancing for *any* given degree of real wage rigidity (Figure 7). Incidentally, a comparison between Figures 7 and 2 also illustrates the gains from optimal monetary policy, which typically halves the magnitude of welfare losses compared to the simple rule.

[Figures 4-7 here]

[11] The calibration of these price mark-up shocks is illustrative. Their standard deviation and persistence parameter are set equal to 0.01 and 0.9, respectively, similar to the values used for technology shocks. It is worth noting that further sensitivity analysis not reported here shows that the shape of the interaction between price stickiness and real wage rigidity would be comparable under wage mark-up rather than price mark-up shocks. The wage mark-up shock enters equation (18) analogously to the price mark-up shock in equation (7) and is specified as AR(1) process analogously to the price mark-up shock in equation (8).

6. Conclusion

This paper explores the welfare effects of real wage rigidities and their interaction with price stickiness, two issues which somewhat surprisingly have surfaced only recently in the New-Keynesian literature. To this end, we rely on a small DSGE model where real wage rigidity results from a combination of staged nominal wage setting and indexation of non-reset wages to past inflation. The benchmark calibration of our simple model captures the main features of U.S. macroeconomic data. Impulse responses to technology shocks are presented, and welfare analysis is undertaken, for a broad range of degrees of price stickiness and real wage rigidity. We find that the welfare cost of real wage rigidities is significantly larger than that from price stickiness. Most interestingly, in a typical "tale of the second best", greater price stickiness can be welfare-enhancing in the presence of real wage rigidities, as it dampens the initial price response and thereby weakens wage indexation mechanisms. These results are shown to be robust to alternative model specifications, shocks and monetary policy assumptions.

From a theoretical perspective, these findings confirm Blanchard and Galí (2007) and suggest that monetary economists should pay greater attention to real wage rigidities than has been the case in the recent past. From a policy perspective, it appears that in the presence of real wage rigidities, reducing price stickiness is not necessarily welfare-enhancing. It is therefore not straightforward that greater product market competition, which is often advocated by central bankers especially in continental Europe, would actually help the conduct of monetary policy unless real wage rigidities are addressed first through labour market reforms.

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Parameter	Symbol	Value
Discount factor	β	0.99
Elasticity of labour supply	φ^{-1}	0.33
Coefficient for disutility of work	κ	1.00
Calvo price stickiness	γ	0.67
Calvo wage stickiness	ω	0.75
Wage indexation	σ	0.70
Elasticity of substitution between goods varieties	η	7.00
Elasticity of substitution between labour varieties	θ	7.00
Input share of capital	α	0.25
Capital adjustment costs	ψ	8.00
Capital depreciation rate	δ	0.025
Shock persistence	ρ	0.90
Standard deviation of innovations	stdev (ν)	0.01

Table 1: Parameters for the benchmark calibration

	Baseline calibration		Actual data	
Variable	Correlation with output	Standard deviation	Correlation with output	Standard deviation
Output	1.000	0.023	1.000	0.017
Consumption	0.998	0.693	0.829	0.628
Investment	0.996	2.716	0.951	2.766
Hours worked	0.873	0.773	0.884	0.847
Real wage	0.721	0.267	0.380	0.469
Inflation	-0.548	0.156	-0.479	0.225

Notes: All variables except inflation are in real terms. The standard deviation for output is the true standard deviation; for all other variables it is the standard deviation relative to the standard deviation of output. Actual data are U.S. quarterly data for 1971q1-2000q4. The actual data for hours worked and real wages refer to the non-farm sector; their correlation with output and standard deviation relate to non-farm output. Actual inflation is the quarterly percentage change of the GDP deflator. Non-farm wages are deflated by the deflator for non-farm GDP.

Table 2: Comparison between the benchmark calibration of the model and actual quarterly data from the U.S. economy

Rigidity parameters		Standard deviations			
Calvo price parameter	Wage indexation	Output	Output gap	Inflation	Nominal interest rate
0.67	0.70	0.0145	0.0012	0.0045	0.0038
0.67	0.40	0.0143	0.0008	0.0037	0.0030
0.90	0.70	0.0126	0.0010	0.0008	0.0015

Table 3: Standard deviations for selected combinations of nominal and real rigidities

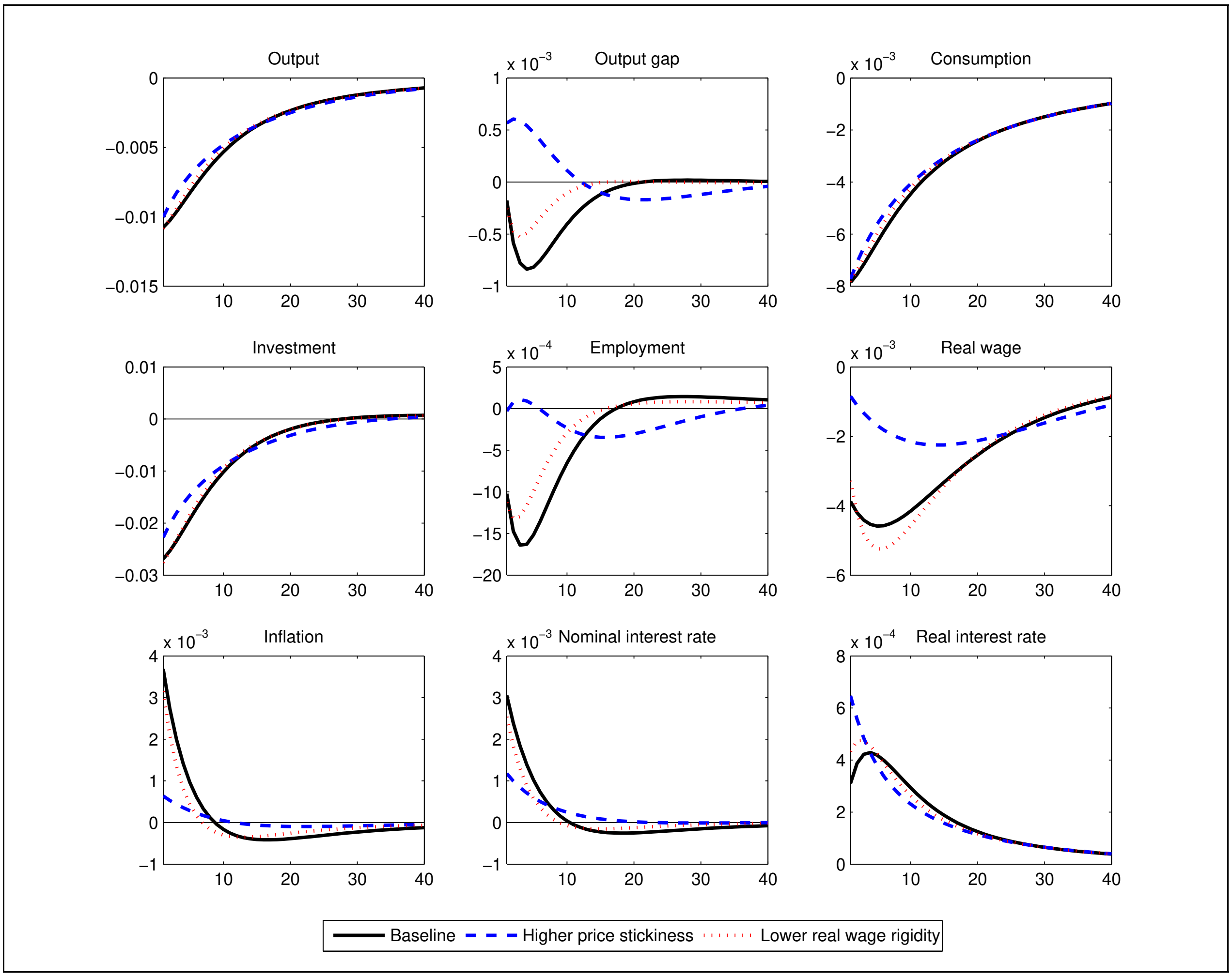

Figure 1: Impulse responses to the technology shock under selected degrees of nominal and real rigidities

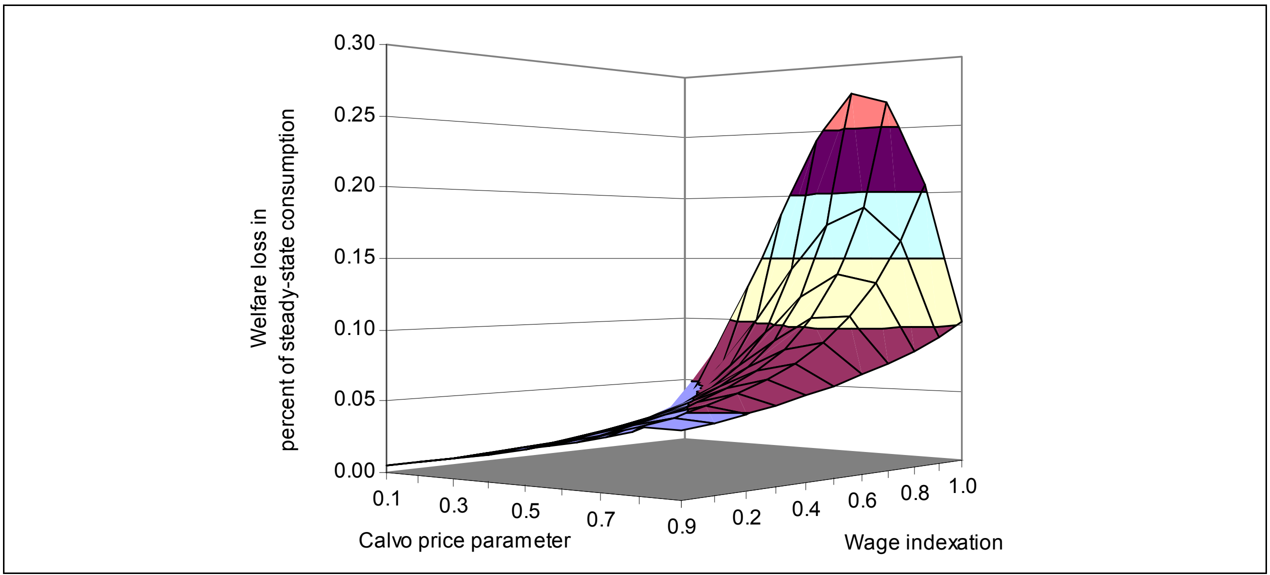

Figure 2: Welfare losses from technology shocks across a grid of price stickiness and real wage rigidity values

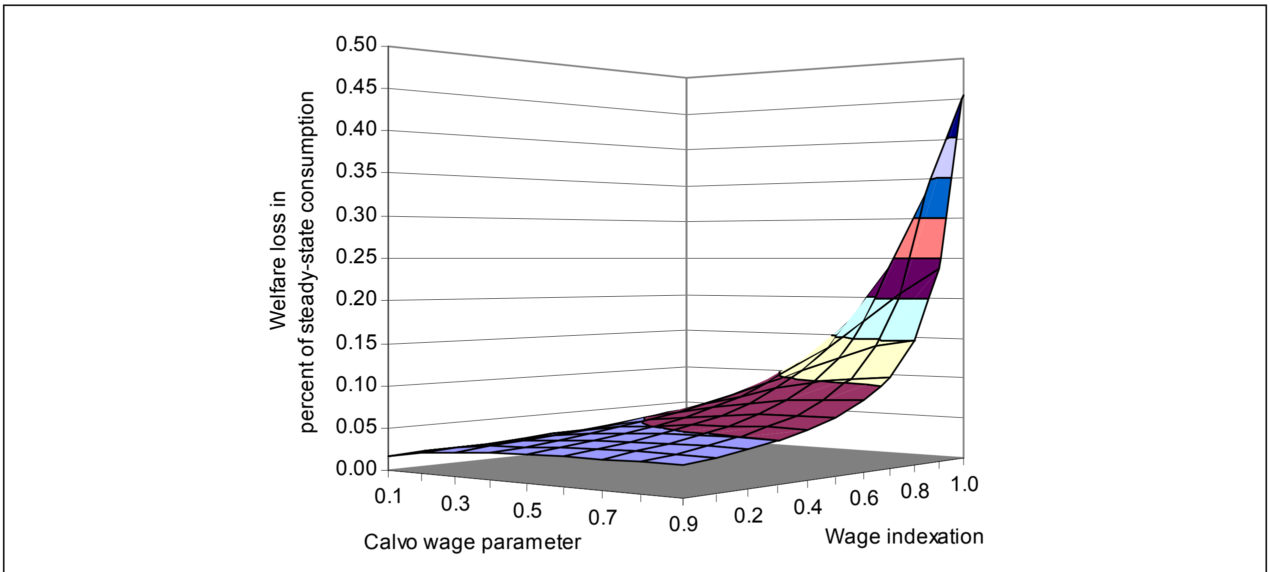

Figure 3: Welfare losses from technology shocks across a grid of nominal wage persistence and wage indexation parameter values

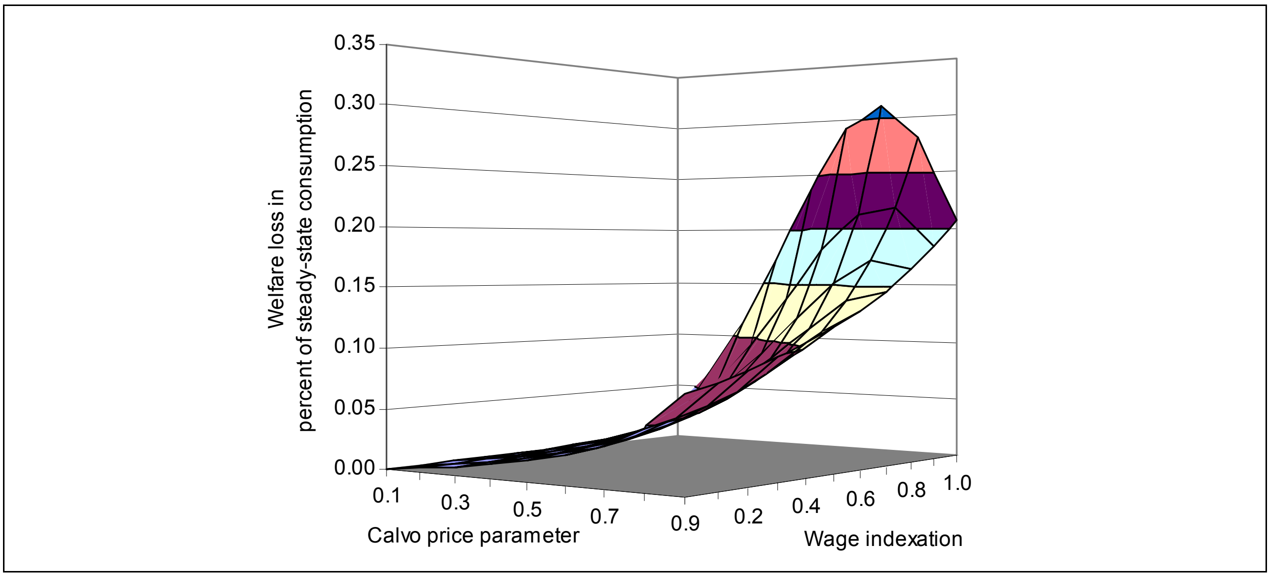

Figure 4: Welfare losses from price mark-up shocks across a grid of price stickiness and real wage rigidity values

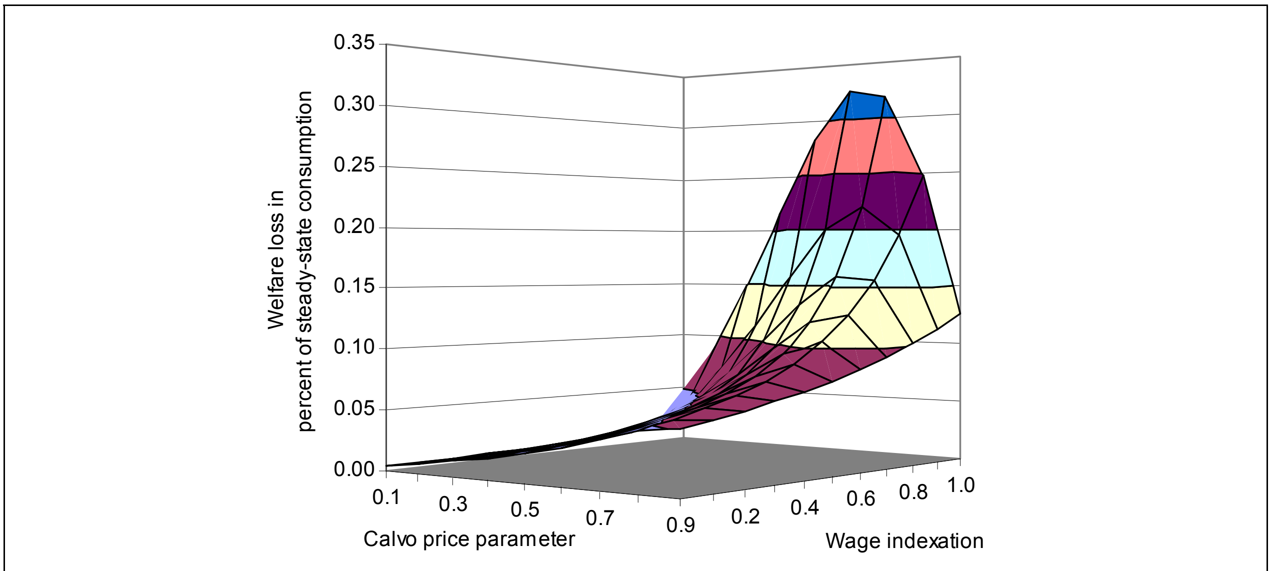

Figure 5: Welfare losses from technology shocks across a grid of price stickiness and real wage rigidity values in a model specification without capital adjustment costs ($\psi = 0$)

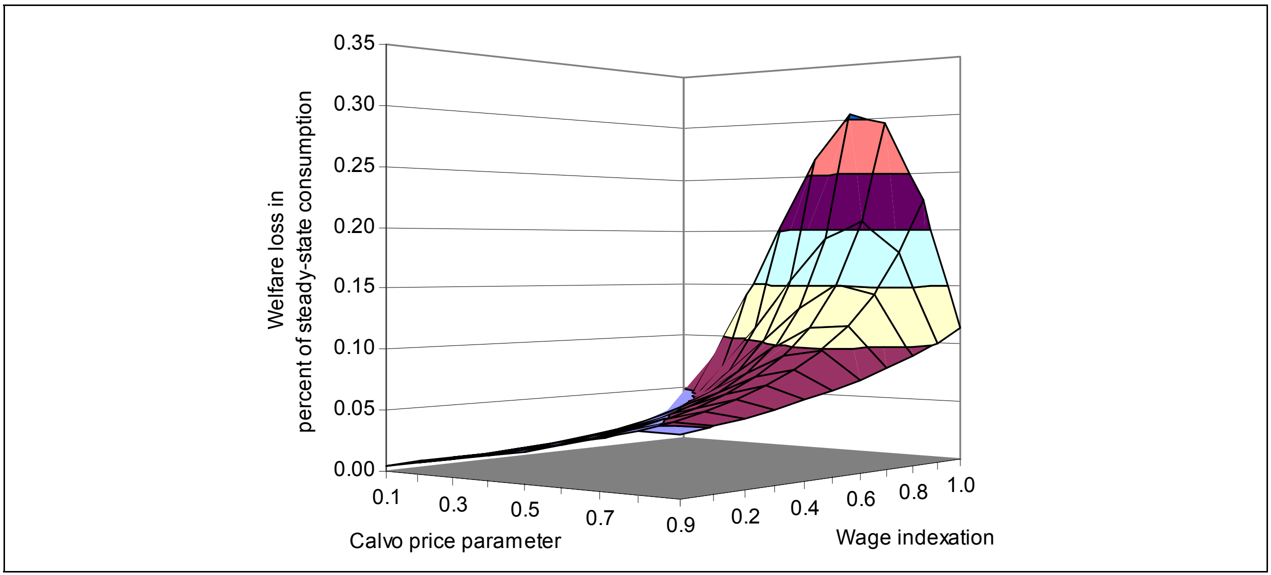

Figure 6: Welfare losses from technology shocks across a grid of price stickiness and real wage rigidity values in a model specification with habit persistence in consumption ($\chi = 0.7$)

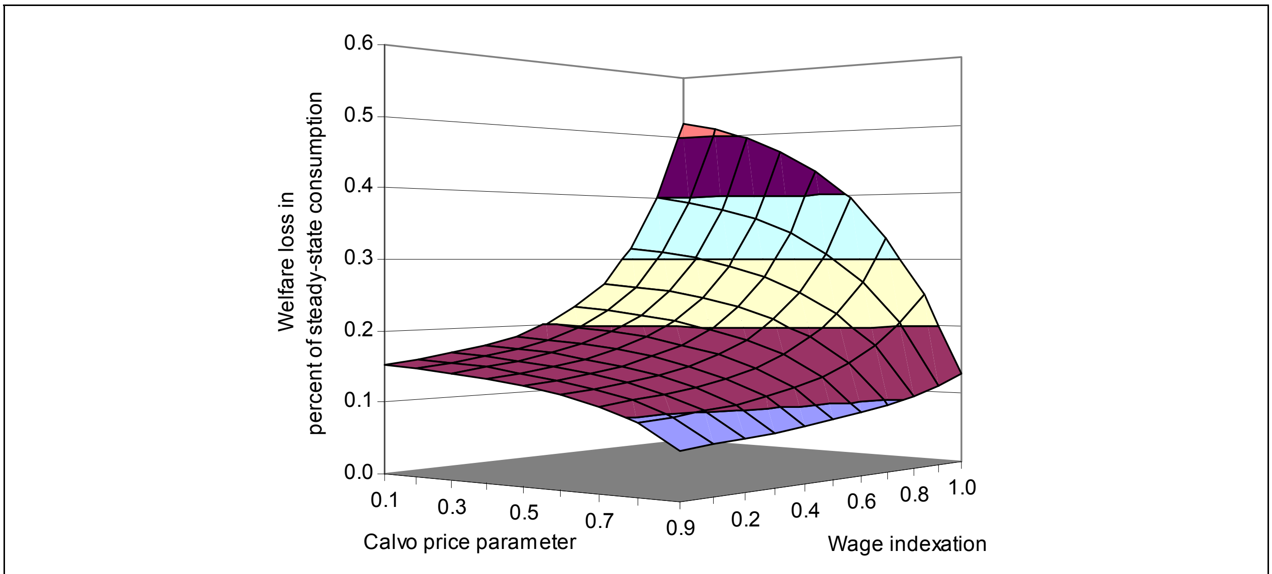

Figure 7: Welfare losses from technology shocks across a grid of price stickiness and real wage rigidity values under a simple interest rule instead of optimal monetary policy