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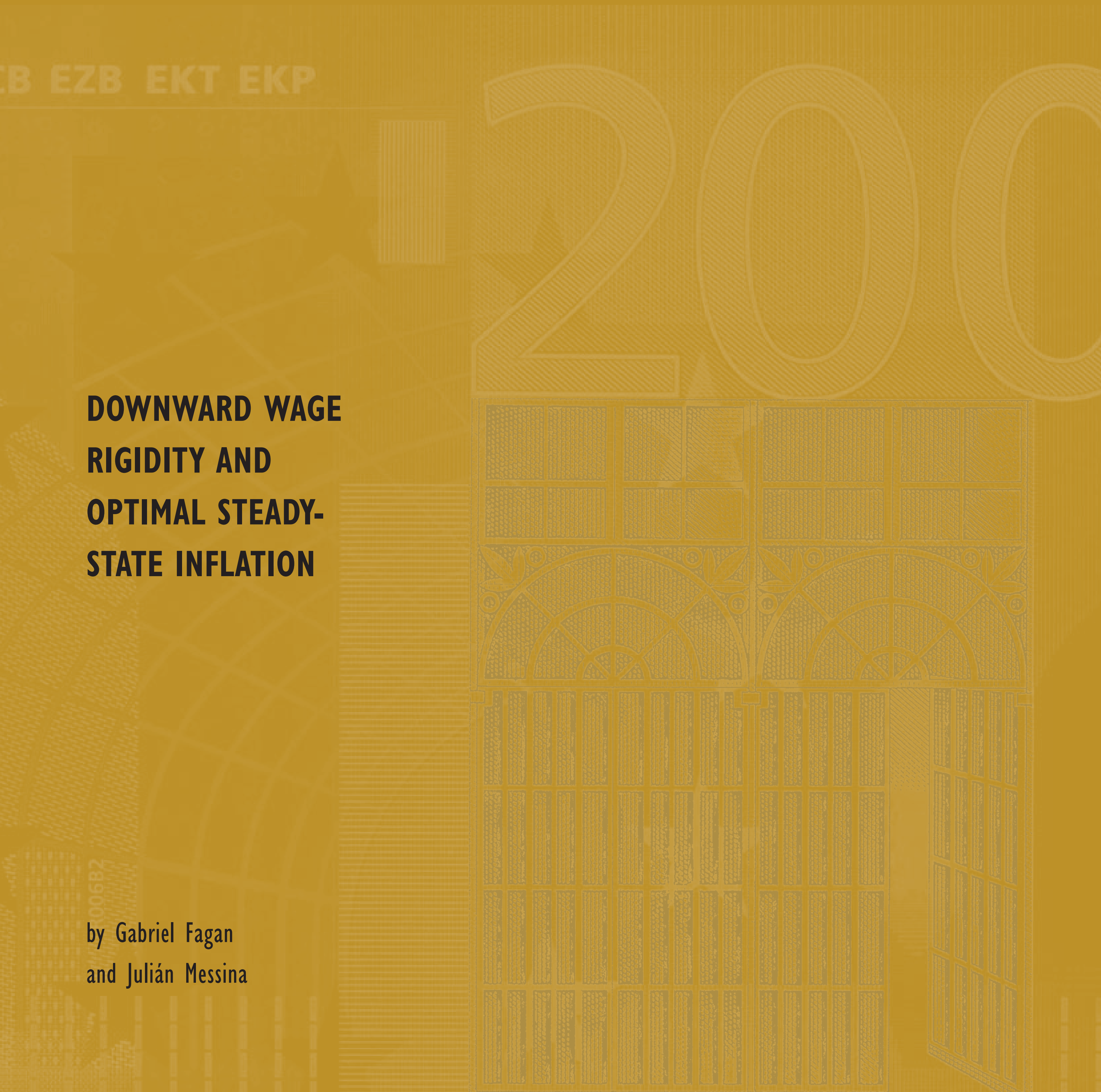

DOWNWARD WAGE RIGIDITY AND OPTIMAL STEADY-STATE INFLATION

by Gabriel Fagan
and Julián Messina

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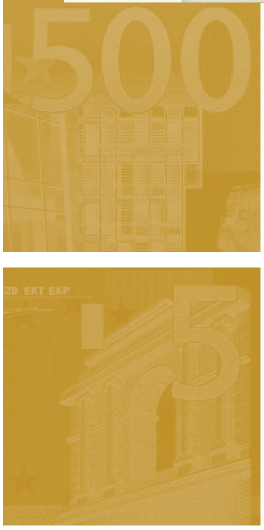
by Gabriel Fagan[2] and
Julián Messina[3]

In 2009 all ECB publications feature a motif taken from the €200 banknote.



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Wage Dynamics Network

This paper contains research conducted within the Wage Dynamics Network (WDN). The WDN is a research network consisting of economists from the European Central Bank (ECB) and the national central banks (NCBs) of the EU countries. The WDN aims at studying in depth the features and sources of wage and labour cost dynamics and their implications for monetary policy. The specific objectives of the network are: i) identifying the sources and features of wage and labour cost dynamics that are most relevant for monetary policy and ii) clarifying the relationship between wages, labour costs and prices both at the firm and macro-economic level.

The WDN is chaired by Frank Smets (ECB). Giuseppe Bertola (Università di Torino) and Julian Messina (Universitat de Girona) act as external consultants and Ana Lamo (ECB) as Secretary.

The refereeing process of this paper has been co-ordinated by a team composed of Gabriel Fagan (ECB, chairperson), Philip Vermeulen (ECB), Giuseppe Bertola, Julian Messina, Jan Babecký (CNB), Hervé Le Bihan (Banque de France) and Thomas Mathä (Banque centrale du Luxembourg).

The paper is released in order to make the results of WDN research generally available, in preliminary form, to encourage comments and suggestions prior to final publication. The views expressed in the paper are the author's own and do not necessarily reflect those of the ESCB.

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CONTENTS

Abstract

This paper examines the impact of downward wage rigidity (nominal and real) on optimal steady-state inflation. For this purpose, we extend the workhorse model of Erceg, Henderson and Levin (2000) by introducing asymmetric menu costs for wage setting. We estimate the key parameters by simulated method of moments, matching key features of the cross-sectional distribution of individual wage changes observed in the data. We look at five countries (the US, Germany, Portugal, Belgium and Finland). The calibrated heterogeneous agent models are then solved for different steady state rates of inflation to derive welfare implications. We find that, across the European countries considered, the optimal steady-state rate of inflation varies between zero and 2%. For the US, the results depend on the dataset used, with estimates of optimal inflation varying between 2% and 5%.

Keywords: downward wage rigidity, DSGE models, optimal inflation

JEL Classification: E31, E52, J4

Non-technical summary

This paper contributes to a long-standing debate in macroeconomics: the implications of downward wage rigidities for the choice of the optimal rate of inflation by a central bank. A traditional argument, which goes back to Tobin (1972), is that, in the presence of downward nominal wage rigidities, a higher rate of inflation will allow easier adjustment of relative (real) wages and will therefore "grease the wheels of the economy". Hence, in the presence of downward nominal wage rigidity, a central bank which aims at an inflation rate which is too low will lead to higher steady state unemployment, thereby reducing welfare. After the original claim by Tobin, a growing body of empirical literature has examined the issue of whether wages are in fact subject to downward rigidity. This evidence has consistently found signs of downward nominal wage rigidity in the US. However, in the case of some European countries, it failed to find evidence of downward nominal wage rigidities; instead, evidence is found for downward real wage rigidities (i.e. a low incidence of real wage cuts). The aim of the present paper is build a bridge between these two strands of literature. We take the empirical evidence as our starting point, and modify an existing DSGE model to allow for a sufficiently flexible wage setting mechanism that is able to match the cross-section of individual wage changes in a wide range of economic environments. In our approach, we do not impose a specific degree of downward wage rigidity; instead, the nature and extent of such rigidities is estimated on the basis of the micro evidence. Specifically, we propose a modified version of the workhorse macromodel of Erceg, Henderson and Levin (2000). In the model proposed here, households are subject to idiosyncratic shocks to their labour productivities, leading them to desire to set different wage rates. However, household wages are subject to a flexible menu cost scheme that incorporates as special cases downward nominal rigidity, downward real rigidity, standard menu costs and flexible wages. A key contribution of the paper is the estimation of the menu cost parameters of the model in order to match the cross-sectional distribution of wage changes observed in individual data. This enables us to take the micro data seriously and examine its aggregate implications in a coherent and consistent manner. We estimate the wage setting parameters of the model by simulated method of moments using individual data for the US, Germany, Portugal, Belgium and Finland,

which have been found to have different degrees of nominal and real wage rigidity. Once parameter values have been estimated and calibrated for the different countries, the model is solved for a number of alternative values of steady state inflation. This allows evaluating a model consistent measure of welfare, and the welfare properties of alternative steady-state inflation rates for different degrees of nominal or real rigidity. We show that our model is able to match pretty well the cross-sectional wage change distributions observed in the data. Once the model has been guided and disciplined by the micro evidence, we compute model consistent welfare maximising steady state inflation rates for each country. We find that for the European countries considered, optimal inflation ranges from 0 (Belgium and Finland) to 2 percent (Portugal) with Germany occupying an intermediate position. The US results are highly sensitive to the dataset employed. With data uncorrected for measurement error, we find an optimal rate of inflation of 2 percent. However, using the estimates implied by the corrected data, we arrive at an optimal rate of 5 percent.

1 Introduction

The recent monetary economics literature suggests that the optimal rate of inflation is either zero or negative. In the context of the canonical New Keynesian model without monetary frictions, a zero rate of inflation maximises welfare since it minimises the distortions caused by staggered price setting and/or the costs of changing prices. If monetary frictions are added to the model, e.g. via cash in advance constraints, then the optimal rate of inflation becomes negative and lies in an interval between zero and the optimal rate predicted by the classic Friedman rule (Schmitt-Grohe and Uribe, 2008). In practice, however, central banks do not aim for zero or negative inflation. In fact, the longer term inflation targets/objectives of central banks typically involve positive (albeit small) rates of inflation (Roger and Stone, 2005). This gap between theory and practice is striking and a number of reasons have been put forward to explain it (a good survey is provided by Palenzuela, Camba-Mendez, and García (2003)).

One of the most prominent arguments in favour of the optimality of a positive rate of inflation is that this will allow easier adjustment of relative (real) wages and will therefore 'grease the wheels of the economy'. This line of thinking goes back at least to Tobin (1972). The argument has been formalized by Akerlof, Dickens, and Perry (1996), who show that in the presence of downward nominal wage rigidity, a central bank which aims at an inflation rate which is too low will lead to higher steady state unemployment, thereby reducing welfare. In the European context, a similar claim is put forward by Wyplosz (2001): 'in order to significantly reduce the (unemployment) effect, the ECB ought to aim at an inflation rate of more than 5%, a rate clearly beyond the current range of acceptability. Simply allowing inflation to be, in the long run, around 4% would go a long way towards eliminating the adverse effect'.

At the same time, there is a growing body of literature examining the issue of whether wages are in fact subject to downward nominal rigidity (see Kramarz (2001) and Yates (1998) for surveys of the earlier evidence, and Fehr and Götte (2005) and the Special Issue in the Economic Journal in November 2007 for different country studies). Most recently, a comprehensive cross-country study has been carried out in the context of the International Wage Flexibility Project (IWFP) (Dickens et al. 2007, 2008) and this work has been extended in a number of directions in the context of the Wage Dynamic Network (Messina et al., 2008). This evidence has identified downward nominal wage rigidity in a number of countries and sectors. Interestingly, in the case of some European countries, there is little evidence of downward *nominal* rigidities; instead, evidence is found for downward *real* rigidities (i.e. a low incidence of real wage cuts).

The aim of the present paper is build a bridge between these two strands of literature. We take the empirical evidence as our starting point, and modify an existing DSGE model to allow for a sufficiently flexible wage setting mechanism that is able to match the cross-section of individual wage changes in a wide range of economic environments. In our approach, we do not impose a specific degree of downward wage rigidity; instead, the nature and extent of such rigidities is estimated on the basis of the micro evidence. Specifically, we propose a modified version of the workhorse macromodel of Erceg, Henderson and Levin (2000) (henceforth the EHL model). This model, and in particular its treatment of wage-setting, has been highly influential for the current generation of DSGE models which are now routinely used in both the academic literature and central banks. A key contribution of the paper is the estimation of the menu cost parameters of the model in order to match the cross-sectional distribution of wage changes observed in individual data. This enables us to take the micro data seriously and examine its aggregate implications in a coherent and consistent manner. For the purpose of estimation, we use IWFP data for the US, Germany, Portugal, Belgium and Finland, which have been found to have different degrees of nominal and real wage rigidity. To achieve our aim, our model modifies EHL in a number of important dimensions.

Most important, the EHL model is extended to allow for the possibility of downward nominal or real wage rigidities. To this end, we replace the Calvo wage setting setup in EHL by one in which the setting of household wages is subject to a flexible menu cost scheme which incorporates as special cases downward nominal wage rigidity, downward real rigidity, standard menu costs and flexible wages. We will further assume that households are subject to idiosyncratic shocks to their labour productivities, leading them to desire to set different wage rates. Our setup thus allows us to generate cross-sectional distributions of wages and wage changes which can be compared to the IWFP results. This gain comes at a price of increased complexity since we have to deal with an heterogenous agent economy. Hence, in order to limit the heterogeneity in the model further, we replace the Calvo setting in prices by quadratic adjustment costs. This implies that each firm in the economy will charge the same price. Finally, our focus is on the steady state whereas EHL were primarily interested in the dynamic adjustment of the economy to shocks. Thus, in order to have a satisfactory account of the steady state, we introduce capital into the EHL model.

The resulting model is solved using heterogenous agent model solution techniques pioneered by Aiyagari (1994) and Huggett (1993). This involves finding a general equilibrium steady state characterised by constant values of the macroeconomic aggregates (consistent with optimisation and resource constraints), an invariant distribution of households across household-specific state variables and consistency between individual behaviour (which is subject to idiosyncratic shocks) and aggregate outcomes. The macro parameters of the model are calibrated, while the wage-setting parameters are estimated from individual data through a simulated method of moments procedure.

Another goal of the paper is to examine the implications of downward nominal and real rigidities for optimal steady state inflation. Once parameter values have been specified and estimated, the model is solved for a number of alternative values of steady state inflation. We can then evaluate a model consistent measure of welfare and the welfare properties of alternative steady-state inflation rates for different degrees of nominal or real rigidity.

There appears to be a growing interest in the macroeconomic impact of downward wage rigidities and this issue has been explored in a number of recent papers. For example, Fahr and Smets (2008) model downward wage rigidity by means of an asymmetric adjustment cost function for aggregate wages and explore the implications for optimal monetary policy in a two-country monetary union. Benigno and Ricci (2008) model downward wage rigidities by assuming a strictly binding non-negativity constraint on aggregate nominal wage changes and examine the implications for the Philips curve and the relation between the volatilities of unemployment and inflation.

The remainder of the paper is structured as follows. Section 2 reviews the empirical evidence on downward wage rigidity available in the context of the IWFP. Section 3 presents the modified version of the EHL model. In Section 4, we characterise the general equilibrium steady-state of this model and outline how it can be computed. Section 5 deals with the selection of parameter values, with a special focus on the estimation of wage rigidities. Section 6 presents the results of the computation of optimal steady-state inflation using the model with alternative estimates of downward rigidities. Finally, Section 7 presents the conclusions.

2 Measuring downward wage rigidity

For measures of downward nominal and real rigidity we rely on the International Wage Flexibility Project (IWFP) methodology and data. The IWFP was a major cross-country research network originally covering 16 countries aiming to produce comparable information on the extent of downward rigidities measured from individual wage changes. The main focus of the project was to identify and quantify downward rigidities (either nominal or real) in wage setting (see Dickens et al. (2007) for a summary). The project was extended in different dimensions within the context of the Wage Dynamics Network, including new datasets and new analyses (see Messina et al. (2008)).

The methodology adopted in the studies is as follows. For each country dataset and each year in the sample, the distribution of percentage wage changes across individuals who have not changed jobs in the period was derived. In order to correct for measurement error, a methodology described at length in Dickens and Goette (2005) was adopted. This methodology aimed at correcting for the different sources of measurement error present in each dataset in order to guarantee, to the extent possible, the comparability of results across countries and data sources. Deviations of the true (error-free) wage-change distributions from a symmetric distribution were used to construct measures of downward nominal and real rigidities.

Our focus in this paper will be on the IWFP results for five countries: the US, Germany, Portugal, Belgium and Finland. The first three countries in this list are characterized by different degrees of downward nominal wage rigidity (DNWR). In contrast, in the last two countries there is little evidence of nominal rigidity but clear evidence or downward real wage rigidities

(DRWR). Details of the data sources in the five countries under study are presented in Table 1. All datasets, with the exception of US data, are obtained from administrative sources. The US data is derived from the Panel Study of Income Dynamics, a household survey that features much smaller sample sizes than in the other four cases, and a larger extent of measurement error. This has a large impact on the estimates of rigidity derived below, depending on whether measurement error has been corrected for or not. Hence, in the case of the US we present results based on both, the raw data and the distributions corrected for measurement errors. In the other four cases, we derive the relevant statistics to be matched from error-free wage change distributions.

By way of illustration, representative histograms of the wage change distributions are presented in the left hand columns of Figures 1 and 2. A notable feature of these histograms (to varying degrees) in the case of the US, Germany and Portugal, is the spike at zero and the lack of mass at wage changes below zero. This is interpreted by Dickens et al. (2007) as evidence of downward nominal rigidity. These features are not apparent in the histograms for Belgium and Finland, where instead there appears to be some bunching of the wage changes in the vicinity of the inflation rate, particularly in the latter country, an indicator of downward real wage rigidity. In both sets of histograms, there is another feature, which has not attracted much attention but which will complicate our modelling of wage setting. Specifically, there is a notable non-zero mass at small absolute wage changes. This feature is inconsistent with pure menu cost models, which would normally imply a 'zone of inaction' and thus lead to the absence of small wage changes.

On the basis of the analysis of the wage-change histograms, the IWFP computed two simple summary measures of rigidity.[1] Note that, in a rather mechanical way, a higher inflation rate would imply a lower spike at zero, since a smaller fraction of workers would have been scheduled for a nominal wage cut. The IWFP researchers sought measures of rigidity that are largely invariant with respect to macroeconomic conditions. Deriving measures of

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[1] We use here the simple measures of wage rigidity as described in Dickens et al. (2007). The IWFP developed a second methodology to estimate downward rigidities based on a mixed method of moments that contrasts the actual (corrected for measurement error) distribution of wage changes with an estimated notional (2-sided Weibull) distribution of wage changes that would have prevailed in the absence of rigidity. See Dickens et al. (2008) for details.

DNWR is straightforward. Assuming that everyone who had a nominal wage freeze would have had a nominal wage cut in the absence of DNWR, it is measured as

$$DNWR = \frac{f_n}{f_n + c_n}$$

where f_n is the fraction of workers with nominal wage freezes and c_n is the fraction with nominal wage cuts. In the analysis below we will match both f_n and c_n separately. Measuring DRWR is more difficult. Probably with the sole exception of Finland, the wage-change histograms shown in Figures 1 and 2 do not present a sharp spike in the vicinity of the inflation rate, as happens with the spike at zero used to measure DNWR. This is not surprising, as inflation expectations are likely to differ across workers and firms. Hence, Dickens et al. (2007) measured DRWR using information on the fraction of observations missing from the lower tail, below the expected rate of inflation, as compared to the equivalent area of the upper tail of the distribution (that is, the area from {median + [median – expected inflation]} to infinity}). Hence, DRWR is measured as

$$DRWR = 2\frac{f_u - f_l}{f_u}$$

where f_u is the fraction of observations in the upper tail of the wage change distribution and f_l is the fraction of observations in the lower tail below expected inflation (π^e), which is approximated by the prediction of a regression on past values. The ratio is multiplied by two to account for the fact that even if the observed rate of inflation coincides with the median of the expected rate of inflation in each year, half of all wage changes will in fact be based on inflation expectations that are lower than actual inflation. If these workers receive a wage change equal to their own expected rate of inflation, their wage change will be below the observed rate of inflation, hence biasing downwards the estimates of DRWR.

Average estimates of the percentage of workers receiving wage cuts, the spike at zero and DRWR are displayed in Table 4. As visual inspection of the histograms suggested, downward nominal wage rigidity dominates in the US, Germany and Portugal, with the US being the country displaying the highest concentration of observations that received zero wage changes. In contrast, all workers in Finland are potentially subject to real rigidity, while the IWFP estimates suggest that real rigidity prevents real wage cuts for nearly 60% of the Belgium workforce.

3 The model

Erceg et al. (2000) presented a microfounded 6-equation DSGE model. The model features monopolistically competitive goods and labour markets with both price and wage setting subject to Calvo schemes. To facilitate aggregation, they assumed existence of a complete contingent claims market for consumption (but not for leisure). This implies that, despite different labour market outcomes, consumption is equal across households. Since their interest was in fluctuations around the steady state, they assumed, for analytical convenience, that the capital stock was fixed. The most notable feature of the model, for our purposes, is the treatment of wage setting. In the EHL setup, households are monopolistically competitive labour suppliers. Facing a downward demand for their specific labour type from a labour aggregator, households set nominal wages as part of their utility maximisation problem. In doing so, they are subject to a Calvo contracting scheme, which implies that each period a fraction of the households are unable to change their wages.[2]

This approach to modelling wage setting has been highly influential. Most of the leading DSGE models which are used for monetary policy analysis in central banks and in the academic literature (for example, Christiano, Eichenbaum, and Evans (2005), Christiano, Motto, and Rostagno (2003), Smets and Wouters (2003), the Federal Reserve Board's Sigma model (Erceg, Guerrieri, and Gust, 2007) and the ECB's New Area-Wide Model (Coenen, McAdam, and Straub, 2008) incorporate this type of wage setting scheme. Given its influential role as a basis for many of the models currently used for monetary policy evaluation, it seems natural to take the EHL model as the starting point for our analysis.

In order to replicate the cross sectional distribution of wages observed in the different country datasets, the main extension we make to EHL relates to the wage setting process. While retaining the feature that wages are set

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[2] An alternative approach, in which firms, rather than households, are the wage setters is developed by Casares (2007)

by households, we modify the household wage setting problem in two crucial respects. First, we assume that households are subject to idiosyncratic (but persistent) productivity shocks. Second, we replace the Calvo scheme for wage setting by a regime in which households are subject to menu costs of changing wages that are potentially asymmetric (it is more costly to cut rather than to increase wages) and stochastic (menu costs will apply only some of the time, determined by a simple Bernoulli process). In order to limit the extent of heterogeneity in the model, we retain the EHL assumption of a complete contingent claims market for consumption (implying that consumption and asset holdings are equal across households). In addition, for the same reason, we replace the Calvo scheme for price setting by one in which firms are subject to quadratic adjustment costs for changing prices à la Rotemberg (1987). This of course implies that all firms charge the same price at each point in time. Finally, since, in contrast to EHL, our focus is on the steady state, we introduce endogenous capital formation.

We consider a single-good closed economy model. In this economy, there is a continuum of monopolistically competitive intermediate goods firms producing output with capital and labour inputs and a standard Cobb-Douglas technology. These intermediate goods are then sold to final goods firms, which bundle them and sell the final goods to households. Final goods firms are assumed to behave competitively. We assume that the intermediate goods firms are subject to quadratic costs of adjusting prices. These firms rent the capital stock from the households while they purchase labour inputs from a standard labour aggregator.

There is a continuum of households owning the capital stock that are subject to idiosyncratic shocks to their productivity (which we assume is given by an $AR(1)$ process). In the labour market, households supply differentiated labour services to the labour aggregator. With risk sharing for consumption in place, households choose paths for consumption to maximise their utility. This implies that all households will have the same level of consumption and wealth. In each household, wages are set by a wage-setter in order to maximise utility, subject to wage adjustment costs and taking as given the level of consumption of the household. Wages are set on a right to manage scheme, which implies that hours worked by the household are on the labour demand curve at all times.

This is a 'cashless economy'. There is a government that consumes final goods and is assumed to balance its budget in each period by levying lump sum taxes on the households. Our focus throughout the paper will be on the steady state of the economy in which there are no aggregate shocks (but of course there are idiosyncratic shocks to individual productivity).

3.1 Final goods firms

Final good firms combine the output of the intermediate good firms using a Dixit-Stiglitz technology. These firms act competitively and their profits are zero. Their first order conditions for profit maximization imply a demand for the output of intermediate firm i given by:

$$y_t(i) = \left[\frac{p_t(i)}{P_t}\right]^{-\epsilon_p} \tag{1}$$

where $p_t(i)$ is the price charged by the i'th intermediate good firm, P_t is the aggregate price index and ϵ_p is the elasticity of substitution across intermediate goods.

3.2 Intermediate goods firms

There is a continuum of intermediate goods firms that employ capital and labour to produce output, which is sold to the final goods firms. The firms are monopolistically competitive and choose their individual prices to maximise the present discounted value of their profits subject to the demand for their product (given by (1)) and a Cobb-Douglas production function.

Specifically, they choose paths for their capital and labour inputs to maximise the expected discounted value of real cash flows:

$$E_t\left[\Sigma_{t=0}^{\infty}\beta^t R_t\right] \tag{2}$$

where β is the discount factor and real profits per period are given by:

$$R_t = \frac{p_t(i)y_t(i) - W_t l_t(i) - r_t^k k_t(i)}{P_t} - c_p\left(p_t(i), p_{t-1}(i)\right) \tag{3}$$

where W_t is the aggregate wage rate, r_t^k the rental price of capital, and the function $c_p\left(p_t(i), p_{t-1}(i)\right)$ reflects the costs of adjusting prices, which is given by:

$$c_p\left(p_t(i), p_{t-1}(i)\right) = \frac{1}{2}\phi_p\left(\frac{p_t(i)}{p_{t-1}(i)} - 1\right)^2 y_t(i) \tag{4}$$

Output is given by the following Cobb-Douglas technology:

$$y_t(i) = \alpha_0 k(i)^{\alpha} l(i)^{1-\alpha}$$

First order conditions with respect to labour and capital are:

$$p_t(i)\left(\frac{\epsilon_p - 1}{\epsilon_p}\right) + \frac{p_t(i)}{y_t(i)}\left(\frac{1}{\epsilon_p}\right)\left(c_p^1 + \beta c_p^2\right) = \frac{W_t}{F_l} \tag{5}$$

$$p_t(i)\left(\frac{\epsilon_p - 1}{\epsilon_p}\right) + \frac{p_t(i)}{y_t(i)}\left(\frac{1}{\epsilon_p}\right)\left(c_p^1 + \beta c_p^2\right) = \frac{r_t^k}{F_k} \tag{6}$$

where c_p^1 and c_p^2 denote respectively the derivatives of the price adjustment cost function (4) with respect to its first and second arguments, while F_l and F_k are the marginal products of labour and capital respectively.

3.3 Households

There is a continuum of infinitely-lived households of unit mass, indexed by $h \in [0, 1]$, which supply their labour to the labour aggregator, own the capital stock and rent it to firms and choose a path for consumption to maximise their expected lifetime utility, which is given by:

$$E_t\left[\Sigma_{t=0}^{\infty}\beta^t\left(\frac{c(h)^{1-\sigma}}{1-\sigma} - \frac{\gamma l_t(h)^{1+\chi}}{1+\chi}\right)\right] \tag{7}$$

Households' wealth takes the form of holdings of the capital stock (k), shares in the intermediate goods firms and a set of state-contingent securities that insures their consumption against adverse labour market outcomes. Their budget constraint is:

$$P_t\left(c_t(h) + i_t(h)\right) + \delta_{t+1,t}B_t(h) - B_{t-1}(h) =$$
$$w(h)l_t(h) + r_t^k k_t(h) + \Gamma_t\left(h\right) - \tau_t\left(h\right)$$

where $c_t(h)$ and $i_t(h)$ are the households consumption and investment expenditures. $w_t(h)$ and $l_t(h)$ are the household-specific wages and hours worked respectively. $k_t(h)$ is the household's capital stock while r_t^k is the rental rate on capital. Each household owns an equal share of all firms, and receives an aliquot denoted by $\Gamma_t(h)$, while $\tau_t(h)$ is a lump sum tax levied by the government. As in EHL, $B_t(h)$ denotes a vector of household holdings of state contingent bonds and $\delta_{t+1,t}$ is a vector of prices of one unit of the corresponding bonds. These bonds provide complete insurance for the household income against household-specific labour market outcomes. Under these conditions, EHL show that household consumption (but not leisure) will be equal across households.

In addition, households are subject to the following capital accumulation equation:

$$k_{t+1}(h) = i_t(h) + (1-\delta)k_t(h) \tag{8}$$

where δ is the depreciation rate. This is a modified version of EHL equation (14) to include capital but excluding money. First order conditions are standard:

$$U_{c_t} = E_t\left[\beta(1+i_t)\frac{P_t}{P_{t+1}}U_{c_{t+1}}\right] \tag{9}$$

where i_t is the nominal risk free interest rate, and U_{ct} the marginal utility of consumption, which, by virtue of the assumptions on risk sharing, is equal across households. The first order condition for the capital stock implies:

$$r_t^k = i_t - E_t\pi_{t+1} + \delta \tag{10}$$

where π_{t+1} is next period's inflation rate.

3.4 The labour market

3.4.1 The labour aggregator

Labour input is supplied to firms via a labour aggregator that combines the labour inputs of the households according to the following Dixit-Stiglitz technology:

$$L_t = \left[\int_0^1 \left(q_t(h)l_t(h)\right)^{\frac{1}{\theta_w}}dh\right]^{\theta_w} \tag{11}$$

where $l(h)$ is labour input from household h and $\theta_w > 1$. A crucial difference from EHL is the introduction of the household's idiosyncratic productivity shock given by the term $q_t(h)$. It is assumed that $q_t(h)$ follows a stochastic process:

$$\log(q_{t+1}(h)) = \rho \log(q_t(h)) + \epsilon_{t+1}(h) \tag{12}$$

The first order condition for cost minimisation by the aggregator implies the following demand for labour of household h:

$$l_t(h) = q(h)^{\frac{1}{\theta_w - 1}} \left(\frac{w_t(h)}{W_t} \right)^{\frac{\theta_w}{1-\theta_w}} L_t \tag{13}$$

Ceteris paribus, an increase in the productivity of an individual household implies an increase in labour demand for that household, while labour demand depends negatively on the relative wage charged by the household. As usual, it is assumed that the labour aggregator behaves competitively, implying that the aggregate wage charged to firms is given by:

$$W_t = \left[\int_0^1 \left(\frac{w_t(h)}{q_t(h)} \right)^{\frac{1}{1-\theta_w}} dh \right]^{1-\theta_w} \tag{14}$$

3.4.2 Wage setting

We assume that there is a wage setter in each household. Each period, the household wage setter chooses the wage rate for its household, taking as given the households consumption path (which, as indicated earlier, is equal across households) and the demand for labour from the aggregator, which is given by (13). Thus we assume a right to manage setup in which the level of hours worked is determined by the labour demand function of the aggregator. Given the household's utility function (7), the household wage setter chooses a path for the wage rate $w_t(h)$ in order to maximise

$$E_t \left[\Sigma_{i=t}^{\infty} \beta^{(i-t)} \phi_t \right] \tag{15}$$

where:

$$\phi_t = \frac{U'(c_t)}{P_t} \left[w_t(h) l_t(h) - c_w(w_t(h), w_{t-1}(h), I_t(h)) \right] - \gamma \frac{l_t(h)^{1+\chi}}{1+\chi} \tag{16}$$

The last term on the right hand side of this expression is simply the disutility to the household from supplying labour services. The remaining part is the real net labour income of the household (wage income minus wage adjustment costs) converted into 'utils' by multiplying by the marginal utility of consumption. In the absence of wage adjustment costs, our setup would imply that the optimal policy for the wage setter would be the standard policy of setting the wage as a markup over the marginal rate of substitution between consumption and leisure. If, instead, the household were subject to a Calvo scheme, the optimal policy of the wage-setter would be identical to the solution obtained by EHL.

In contrast, with a view to matching the cross-sectional distribution of individual wages observed in the data, we assume that the wage-setter is subject to a stochastic asymmetric menu cost. In the most general case, the cost of changing wages is given by:

$$c_w\left(w_t(h), w_{t-1}(h), I_t(h)\right) = \begin{cases} I_t(h) c_+ W_t & \text{if } w_t(h) > w_{t-1}(h)) \\ I_t(h) c_- W_t & \text{if } w_t(h) < w_{t-1}(h) \\ I_t(h) c_R W_t & \text{if } \left(\frac{w_t(h)}{w_{t-1}(h)}\right) < (1+\pi_t) \\ 0 & \text{if } w_t(h) = w_{t-1}(h) \end{cases} \tag{17}$$

where $I_t(h)$ is an *iid* Bernoulli variable given by:

$$I_t(h) = \begin{cases} 1 \text{ with prob } p \\ 0 \text{ with prob } (1-p) \end{cases} \tag{18}$$

and c_+ is the cost of changing the wage (as a percent of the aggregate wage) when the wage is increased. c_- is the cost of changing the wage when the wage is decreased. If $c_- > c_+$ then there is downward nominal rigidity, whereas if these two parameters are equal, the model reduces to a standard menu cost setup. c_R is the cost of increasing wages at a rate below the inflation rate (π_t). This parameter captures potential downward real rigidity on the part of households (i.e. an unwillingness to undergo real wage cuts). The stochastic element in the cost function is introduced for the following reason. In a standard menu cost setting, the optimal decision rule would involve a zone of inaction in which wages would not be changed unless the shocks to productivity were sufficiently large. This would imply that we would not observe small wage changes in the data, a feature that is not consistent with most of the observed wage change distributions analyzed in the context of the IWFP. Stochastic menu costs allow us to overcome this limitation. The particular form chosen, an *iid* Bernoulli process, is the simplest way of introducing this element in order to match the data.

Normalising real variables by dividing by aggregate trend productivity (and, for nominal variables, the aggregate price level) to arrive at a stationary model, the problem of the wage setter can now be expressed as a standard dynamic programming problem with the value function given by:

$$V\left(q_t(h), \tilde{w}_{t-1}(h), I_t(h); \Theta\right) = \underset{\tilde{w}_t(h)}{Max}\left[\phi_t + \beta E_t V\left(q_{t+1}(h), \tilde{w}_t(i), I_{t+1}; \Theta\right)\right] \tag{19}$$

where the maximisation is carried out with respect to $\tilde{w}_t$, the normalised household wage rate.

The value function depends on a set of parameters (Θ) and 3 household-specific state variables: the current period idiosyncratic shock $(q_t(h))$, the previous period's wage set by the household $(\tilde{w}_{t-1}(h))$ and the Bernoulli variable $(I_t(h))$, which indicates whether the household is subject to menu costs in the current period. The parameter vector (Θ) entering into the value function includes the relevant parameters of household preferences and firm behaviour. It also includes the values of the aggregate macroeconomic variables, which influence the wage-setter's choice of the household wage rate. Since we are focussing on the case of a stationary state, these aggregate variables will all be constant at their steady state values and are treated as parameters by the wage-setter.

The solution to the wage-setter's dynamic programming problem is a decision rule for the current period wage rate to be charged by the household:

$$w_t(h) = G\left(q_t(h), w_{t-1}(h), I_t(h) | \Theta\right) \tag{20}$$

The optimal wage depends on the current period idiosyncratic productivity, the wage set in the previous period and the state variable that indicates whether or not the household is subject to menu costs in the current period. The properties of decision rules in the context of menu cost models have been extensively studied in the context of inventory behaviour and investment (see, for example, Stokey, Lucas, and Prescott (1989) and Dixit and Pindyck (1994)). They have also been applied to price-setting problems (e.g. by Golosov and Lucas (2007) and Nakamura and Steinsson (2006)). In the case of downward nominal wage rigidity, Elsby (2006) develops a model in which downward nominal rigidity of wages is captured by a menu cost for cutting wages and explores its properties.

Typically, the resulting decision rule is characterised by a 'zone of inaction': for sufficiently small shocks, agents do not change the wage, since the discounted gains from doing so would not offset the value of the menu cost. When shocks become sufficiently large, however, they induce agents to change wages in line with the changes that would occur in the absence of frictions. When the menu costs are asymmetric, the resulting zone of inaction will also be asymmetric. For example, with downward nominal rigidity, agents would require larger shocks to induce them to cut wages than to increase wages. To illustrate, Figure 3 shows an example. The figure shows two decision rules: when the wage-setter is subject to menu costs and when menu costs are absent. The latter rule is straightforward. In the absence of menu costs our model predicts that the wage chosen by the household is simply a (log) linear function of the idiosyncratic productivity shock. In contrast, when menu costs apply, an asymmetric zone of inaction will apply. Relatively small positive shocks are sufficient to induce the agent to raise wages. In contrast, negative shocks need to be rather large before the agent will cut wages.

4 General Equilibrium

We concentrate on the case in which the only source of uncertainty is the idiosyncratic shocks to the productivity of the individual households. Then, the steady state of the model described above is given as the solution to the following system of equations, where a $\tilde{}$ over a variable denotes the value of the variable scaled by the level of productivity (we assume zero population growth).

1. The national accounts identity that total expenditure equals output:

$$\tilde{Y} = \tilde{C} + \tilde{I} + \tilde{C}_G - \tilde{C}_w - \tilde{C}_P \tag{21}$$

   where $\tilde{Y}$, $\tilde{C}$, $\tilde{I}$ and $\tilde{C}_G$ are output, private consumption, investment and government consumption (all scaled by trend aggregate productivity). $\tilde{C}_w$ and $\tilde{C}_P$ denote respectively the steady state values of the costs of adjusting wages and prices. Clearly, both of these magnitudes depend on the steady state rate of inflation.

2. The steady-state of the capital accumulation equation (8):

$$\tilde{I} = (\delta + g)\tilde{K} \tag{22}$$

   where g is aggregate trend productivity growth and δ is the depreciation rate.

3. From the consumer's Euler equation (9), we obtain an expression for the steady state real interest rate (r):

$$r = \frac{(1+g)^{\sigma}}{\beta} - 1 \tag{23}$$

4. In steady state, the firm's first order conditions for labour and capital ((5) and (6)) become:

$$L = (1-\alpha)\frac{\tilde{Y}}{\mu_p \tilde{W}} \tag{24}$$

$$\tilde{K} = \alpha \frac{\tilde{Y}}{\mu_p (r+\delta)} \tag{25}$$

   where μ_p is the steady state markup of prices over marginal costs.[3]

5. Finally, the production function is given by:

$$\tilde{Y} = \alpha_0 \tilde{K}^{\alpha} L^{1-\alpha} \tag{26}$$

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[3] Given our assumptions on the quadratic costs of price adjustment as in (4), the expression for the markup is given by $\mu_P = \frac{\epsilon_P}{\epsilon_P + 1 - \phi_p \pi(1+\pi) + \beta \phi_p (1+g)\pi(1+\pi)}$. In the case of zero steady state inflation, this reduces to the standard expression, $\mu_P = \frac{\epsilon_P}{\epsilon_{P+1}}$ where ϵ_P is the price elasticity of demand for intermediate goods firms.

Following Huggett (1993) and Aiyagari (1994), we can define the stationary equilibrium of this economy. In our setup, this corresponds to a situation in which all aggregate variables and the joint distribution of individual wages and productivity are constant over time, while households and firms optimality conditions and resource constraints are satisfied. While aggregate variables are constant, households are subject to idiosyncratic productivity shocks, so that for the individual household wages and hours worked differ over time. Specifically, for a given set of parameters (including π and g), a stationary equilibrium for this economy is a value function for the household wage setter and an associated decision rule for wages $G(q, w_{t-1}, I)$, aggregate quantities $\left\{\tilde{Y}, \tilde{C}, \tilde{I}, \tilde{K}, L\right\}$ and aggregate factor prices $\{r, W\}$, such that:

1. The representative intermediate firm maximises profits, so (24) and (25) hold.
2. Households optimise. Given the aggregate variables, the decision rule $G(q, w_{t-1}, I)$ solves the household wage setter's problem and the interest rate is given by the household's Euler equation (23).
3. The goods market clears (21).
4. Consistency between household wage choices and the aggregate wage:

$$W_t = \left[\int_0^1 \left(\frac{w_t(h)}{q_t(h)}\right)^{\frac{1}{1-\theta_w}} dh\right]^{1-\theta_w} \tag{27}$$

5. The labour market clears

$$L = \left[\int_0^1 (q(h)l(h))^{\frac{1}{\theta_w}} dh\right]^{\theta_w} \tag{28}$$

6. The governments budget constraint is balanced ($\tilde{C_G} = \tilde{\tau}$)
7. There is a stationary joint distribution $F(w, q)$ of $[w(h), q(h)]$.

To compute the stationary equilibrium of the model we proceed as follows (see the Appendix for more computational details). First, we pick a set of parameters. With these parameters, (23) gives us the steady state interest rate. We can then use (24) to (26) to derive the steady state economy-wide wage rate:

$$\bar{W} = \left[\frac{\alpha_0 \alpha^{\alpha}(1-\alpha)^{1-\alpha}}{\mu_p(r+\delta)}\right]^{\frac{1}{1-\alpha}} \tag{29}$$

Second, we pick a starting value for aggregate hours worked. Third, with this value, we use equations (21) to (25) to determine the steady state values of $\left\{\tilde{Y}, \tilde{C}, \tilde{I}, \tilde{K}\right\}$. Fourth, using the resulting steady state values, we solve the dynamic optimisation problem of the wage setter. To compute the solution, we chose discrete grids for $w(h)$ and $q(h)$ and solve the wage-setter's problem using discrete state dynamic programming. Fifth, using the decision rule that solves this problem combined with the stochastic process for q, we derive the invariant joint distribution for $w(h)$ and $q(h)$:

$$F(w_i, q_i) = \text{Prob}\left(w_{t-1}(h) = w_i, q_t(h) = q_i\right) \tag{30}$$

Sixth, we use a discrete approximation of (14) to aggregate across households and to arrive at a model-consistent measure of the aggregate wage rate. If this wage is not equal to the steady state wage given by (29), we chose a new value for hours worked and iterate until both measures of wages are equal.

Following Holden (2005), we can illustrate the determination of the general equilibrium in the steady state and the implications of downward wage rigidities using a simple diagram in the aggregate wage - aggregate hours space. In Figure 4 the horizontal line is the long run demand for labour (or, alternatively, the price setting equation). Since prices are set as a fixed markup (μ_p) over marginal costs, and the marginal product of labour is constant in the long run (adjusted for trends in productivity) the steady state wage rate is also constant (as shown in 29) and can be expressed as the inverse of the price-markup times the marginal product of labour.

Turning to wage setting, let the locus (W_1W_1) indicate the aggregate wage that would come from household wage-setting, at different levels of hours worked (L), in the absence of wage adjustment costs. In this case, each household would set a wage equal to a markup over its marginal rate of substitution between consumption and leisure. In this frictionless case, equilibrium is given by the point A with hours worked at L_1. Even without wage adjustment costs, household market power in setting wages would give rise to a distortion in the labour market, and the resulting level of wages would be above (and hours worked, below) the socially optimal level. The presence of downward wage rigidity is likely to exacerbate this distortion. If downward rigidity (either real or nominal) binds for some households who have been affected by adverse idiosyncratic productivity shocks, they would not be willing to set their wages at the frictionless level (i.e. they will not cut their wages). Hence, average wages in the economy would be higher for any given level of hours worked. As a result, the wage setting curve under binding downward wage rigidity, (W_2W_2), will be to the left of the frictionless curve. Hence, equilibrium hours worked would be lower.

How are these distortions related to the rate of inflation? Consider first the case of downward nominal wage rigidity. As steady-state inflation falls, downward nominal wage rigidity will become more binding for households. Thus as inflation falls, the (WW) curve will shift more and more to the left, leading to less hours worked. Lower inflation, therefore, will be associated with higher levels of the aggregate labour market distortion. This grease effect of higher inflation is what Tobin (1972) had in mind. In contrast, when downward real wage rigidity is the only friction affecting household wage setting, changes in the steady state inflation rate will not alter the incidence of downward rigidity across households. Thus the (WW) curve would not shift in response to changes in the inflation rate.

The effect of changes in the steady state rate of inflation on the aggregate labour market distortion, and thus on hours, will be an important, but not necessarily the dominant component influencing the welfare gains or losses from different steady-state inflation rates, which are examined below.

5 Calibration and estimation of wage-setting parameters

The period of the model is annual. We calibrate the model following a twin track approach. A subset of the parameters (e.g. the rate of time preference, intertemporal rate of substitutions, etc.) is selected from standard values in the literature, or matching features of the aggregate data. The key parameters of our problem, those related to the household's wage setting technology, are estimated from individual data on wage changes, using a simulated method of moments methodology. The values of both sets of parameters are shown in Tables 2 and 3.

5.1 Calibrated parameters

As regards the households utility function, we assume that utility is logarithmic in consumption (implying a value of $\sigma = 1$). The coefficient on labour in the utility function (χ) is set to 1.5, close to the posterior mean reported by Smets and Wouters (2007). This implies a Frisch elasticity of labour supply of $\frac{2}{3}$. The elasticities of the aggregators' demand for both labour (θ_W) and intermediate goods (ϵ_P) are both set to -11, implying steady state markups of 10%. The coefficient γ in the utility function is a normalising constant, chosen to yield a steady state level of hours of unity in the absence of costs of adjusting prices and wages. We assume an annual discount factor (β) of 0.95. In order to match the data for the US economy regarding the shares of investment and government consumption in output over the period 1987-1997, the depreciation rate (δ) is set to 0.08 while the share of government consumption is set to 0.19. The share of capital in the production function (α) is set to the standard value of 0.3. As regards the parameter governing the costs of changing prices ϕ_P in (4) we adopt the following procedure. As is well known (see, for example, Khan (2005)) there is an isomorphism between the Phillips Curve generated by price setting under Calvo contracting and under quadratic adjustment costs.[4] We assume a value for the Calvo parameter (which gives the percentage of firms unable to change their price each quarter) of 0.63, a simple average of the estimates reported by Smets and Wouters (2007) and Christiano, Eichenbaum, and Evans (2005). This, together with the other parameter values indicated above, implies a value of ϕ_P of 45 (in quarterly terms).[5] Finally, we set ρ, the AR1 coefficient in the process for idiosyncratic productivity shocks in (12) equal to 0.9. This lies

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[4] However, while up to a first order Rotemberg and Calvo price setting may generate identical Philips curves, this does not necessarily imply that they have the same welfare implications (see Lombardo and Vestin (2008) for an example). In the Rotemberg setup all firms charge the same price, so there is, in contrast to the Calvo approach, no distortion coming from the fact that firms charge different prices for the same product. On the other hand, since changing prices does not involve a physical cost in the Calvo setup, there are no deadweight losses from changing prices in this case, differently from Rotemberg pricing.

[5] Let ζ_p denote the Calvo parameter (i.e. the percentage of firms not changing price each quarter). As shown by Khan (2005), this implies a value for ϕ_P given by $\phi_P =$

in the midpoint of the estimates of the persistence of labour income for the US reported by Guvenen (2007).[6]

5.2 Estimation of the wage-setting parameters

The key parameters in our study are the household wage setting parameters $\{p, c_+, c_-, c_R \text{ and } \sigma_\epsilon\}$, which are estimated employing the indirect inference method proposed by Gourieroux, Monfort, and Renault (1993). Specifically, for a given set of parameter values, and values for relevant macroeconomic aggregates,[7] we solve the household's wage setting problem using value function iteration and derive the associated decision rule of the household. Given this rule and the stochastic process for idiosyncratic productivity, we can derive the implied stationary distribution for $\{w(i), q(i)\}$.[8] We then derive the stationary distribution of percentage wage changes. We chose values for our five parameters to minimise the distance between the moments generated by the model $\left(m^M\right)$ from the moments obtained from the individual data on actual (or estimated error free) wage changes $\left(m^D\right)$, where the distance is given by:

$$\left(m^M - m^D\right)' \Omega \left(m^M - m^D\right) \tag{31}$$

The moments that we match are: the standard deviation of wage changes, the proportion of wage changes that are zero, the proportion of wage changes that are less than zero, the mean wage increase and the mean wage decrease. In addition, in the case where we are investigating real wage rigidity, we also include either the IWFP indicator (DRWR) described above or the percentage of wage changes below the inflation rate.[9]

$\frac{-(1+\epsilon_P)\zeta_P}{(1-\zeta_P)(1-\beta\zeta_P)}$

[6] Dickens and Goette (2005) assume that the log of individual earnings follows a random walk, which would correspond to $\rho = 1$. We do not follow this approach since it would imply that there would not exist a stationary distribution of (log) wages.

[7] In particular, for the estimation we use the sample averages in each of the countries for productivity growth and inflation (see Appendix for further details).

[8] In order to solve the household's problem we need aggregate values for the variables: detrended real wages and consumption as well as inflation and productivity growth. For these we use averages of macro data for the period obtained from the FRED database of the Federal Reserve Bank of St. Louis for the US and the European Commission's AMECO database for European countries.

[9] Given the computational burden involved and the prior information available from the IWFP, we do not attempt to estimate all 5 parameters using all of the moments listed above. For cases involving nominal rigidity (US, Germany, Portugal), we do not

We assume that the $\epsilon_t(i)$ are distributed as *iid* Laplace, a special case of the two-sided Weibull distribution employed by Dickens et al. (2007). We approximate the AR process for idiosyncratic productivity by using the Marked chain approach of Tauchen (1986). In implementing our indirect inference algorithm we set $\Omega = I$.

Table 4 presents the moments calculated from the data while Table 5 shows the moments implied by the various country models given the estimated parameters. In addition, Figures 1 and 2 show representative histograms of the wage change distribution based on individual data (left columns) and the histograms generated by the model (right columns) for the respective country.

The first observation from these results is that, overall, the models appear to do a good job in matching the moments of the wage change data and in generating histograms which are reasonably close to those of the data.[10]

In regard to the specific parameter estimates a number of comments are in order. First, in line with Dickens et al. (2007), there appears to be convincing evidence of downward nominal rigidity in the US, Germany and Portugal. In contrast, Finland exhibits clear signs of downward real wage rigidity. In the case of Belgium, our results suggest some weak evidence of downward real rigidity.

Looking at the results in more detail, for the US we have two datasets, the IWFP data without correction for measurement error (denoted US 1) and the dataset with correction for measurement error (denoted US 2). For US 1, the parameter p is estimated at 0.49, suggesting that households are subject to menu costs just half of the time. The estimated values of the menu cost parameters point to a cost of decreasing wages which is ten times larger than the cost of increasing wages, thereby consistent with the existence of downward nominal rigidity. The estimated value of the parameters suggests that the cost of reducing wages to the household amounts to some 10% of

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use moments measuring real rigidity and estimate only parameters relevant to nominal rigidity. In the case of real rigidity (Belgium and Finland), we estimate only parameters relevant to real rigidity using the following moments: standard deviation, DRWR or, in the case of Finland, the percent of observations below the inflation rate.

[10] In the case of Germany, however, the model has some difficulties matching the low incidence of small positive increases found in the data (which could either reflect real wage rigidity or menu costs for positive wage changes).

the average wage, a sizeable amount.

The second dataset (US 2) implies a very high degree of downward nominal wage rigidity. The probability of menu costs applying is much higher (0.8) while the estimated cost of cutting wages amounts to nearly 40% of the average annual wage in the economy.

For Germany, downward nominal wage rigidity is found to be much less than in the US. The estimated cost of cutting wages in the presence of menu costs amounts to 2 percent of the annual wage. In Portugal, downward nominal rigidity is found to be more than twice as high as Germany and the probability of menu costs applying is also notably higher.

There is clear evidence of real wage rigidity in the case of Finland. The cost of cutting real wages in the presence of menu costs are sizable, at 7% of the annual average wage, but more importantly real rigidity applies to all workers (p is equal to 1). In Belgium, the evidence from both the histograms and the estimates suggests a rather mild degree of downward real rigidity, in comparison.

6 Computation of optimal steady-state inflation

In the stationary state of the model outlined above, the set of households enjoy the same level of consumption, savings and wealth by virtue of our assumption of complete markets for consumption. However, households differ in regard to their labour market situation. Due to the presence of idiosyncratic productivity shocks, wages and hours worked differ across households. This heterogeneity is summarised by the invariant distribution of (w, q) given by (30). For our analysis we use a Benthamite welfare function adding up the welfare of the different households. This is computed by aggregating utility across households using the invariant distribution as a counting scheme:

$$U = \frac{C^{1-\sigma}-1}{1-\sigma} - \gamma \left(\Sigma_{i=1}^{N_w} \Sigma_{j=1}^{N_q} F_{i,j} \frac{l_{i,j}^{(1+\chi)}}{(1+\chi)} \right) \tag{32}$$

For the different cases we have examined, we compute welfare at different steady state inflation rates using the following procedure. First we take a grid of possible inflation rates, specifically we consider inflation rates between

-3% per annum and +6% per annum. In order to ensure comparability across countries, we assume that, apart from the wage-setting parameters, all of the remaining parameters are equal across countries (as given in Table 2). We also set steady-state productivity growth to a common value, 1% per annum, for all countries. Given the computational burden involved in the calculations, we confine ourselves to integer values of the inflation rate. Second, for each inflation rate we solve the model as described in Section 4 and compute welfare using (32).

The differences in welfare due to different steady state inflation rates may be decomposed into the following elements:

1. Markup: the aggregate labour market distortion as discussed in Section 4. In the presence of downward wage rigidity, changes in the inflation rate lead to changes in the effective markup of the aggregate wage over the marginal rate of substitution. This leads to changes in total hours worked, output and consumption, affecting household welfare.
2. Labour distortion: the presence of menu costs leads households to set wages at levels which differ from the frictionless wage. As a result, the allocation of hours across households (given by its labour demand function), for a given level of aggregate hours, will not be socially optimal. This distortion, which is analogous to the price distortion that arises under Calvo price-setting, can be computed by solving a central planners problem for allocating a given level of total hours across households and comparing it with the actual allocation across households.
3. Adjustment costs for prices: the deadweight costs to society of non-zero inflation due to the assumed quadratic costs of changing prices. This is the so-called ‘sand’ effect of inflation, which counteracts the grease effects mentioned above.
4. Adjustment costs for wages: the deadweight costs to society stemming from the menu costs of changing wages, which, like price adjustment costs, are assumed in our setup to reduce the amount of produced resources available for consumption.

In the absence of any costs of changing wages, the optimal rate of inflation will be zero (due to factor (3) above) since this is the rate that minimises the costs of changing prices, in line with the predictions of the New Keynesian model mentioned in the introduction. Similarly, if wage rigidity takes the form of downward real wage rigidity, then the optimal rate of inflation will also be zero. This is the case since changes in the inflation rate - a nominal variable - do not affect the incidence of wage adjustment costs in the economy. In the presence of downward nominal rigidity the optimal rate of inflation will be greater than zero in our model. It will occur at the level that balances the welfare costs due to wage adjustment, (1), (2) and (4) above, with the costs of non-zero inflation due to (3).

Figures 5 to 12 illustrate the results of the computation. The figures show, for each rate of inflation in the chosen grid: the levels of welfare, output, consumption and employment. In addition, to illustrate the effects of inflation on the wage change distribution we also show the percentages of zero wage changes and negative wage changes. Finally, the three key components influencing welfare complete the picture: the labour distortion (item (2) above), the costs of changing prices and the costs of changing wages. Where relevant, we also show how the changes in welfare are decomposed into the four factors outlined above.

The first example (Figure 5) shows the case where there are no wage adjustment costs. As expected, welfare attains its maximum at zero inflation. Interestingly, output and employment are lowest at this point. This simply reflects the fact that, the more inflation departs from zero, the more agents must work in order to offset the adverse effects on their utility of the deadweight costs of price adjustment.

The next example (Figure 6) show the results for a stylised case involving only real wage rigidities (in particular we set $c_R = 0.1$, implying a cost of cutting real wages amounting to 10% of the average wage). We see in this case that the optimal rate of inflation is zero, confirming the arguments made earlier.

We move next to the relationship between inflation and welfare in our estimated models. Let us first consider US 1: the US data without adjustment for measurement error (Figure 7). Here, welfare attains its maximum at an inflation rate of 2% per annum. At negative or small positive rates of inflation, the costs of changing wages and the labour distortion are high.

As inflation rises, these elements decline tending to raise welfare. However, beyond zero inflation, these welfare gains are increasingly offset by the sand effects of inflation, due to the costs of changing prices. Output and hours worked rise as inflation increases, primarily reflecting a diminishing aggregate labour market wedge as downward nominal rigidity becomes less binding. In this vein, we also observe a decline in the share of zero wage changes. Figure 8 shows the decomposition of these welfare changes according to the four components listed above. The baseline case is an inflation rate of -3%, the lowest rate we consider. Increasing inflation from this low level leads to sizeable gains in welfare, which reach a peak at the optimal rate of 2%, where welfare (measured in consumption equivalents) is some 2% higher than the baseline. The main sources of the gain are the reductions in the labour market markup and in the wage adjustment costs. Over the range of inflation rates the contribution from savings on wage adjustment costs increases monotonically. This reflects the estimated asymmetry of these costs combined with the fact that higher inflation rates reduces the incidence of nominal wage cuts. It is worth noting that the differences in welfare between the optimal inflation rate and inflation rates in the vicinity of the optimal rate are rather small.

The case of Portugal (Figure 11) is similar to the previous one, with welfare reaching its maximum at 2% inflation. The decomposition of welfare changes in the Portuguese and US 1 cases are, as one would expect comparing the estimated parameters, similar (Figure 12)

In the case of Germany, a country presenting a lower degree of downward nominal rigidity than Portugal according to our estimates, the optimal rate of inflation is estimated at 1%. Here, as well, welfare differences between the optimal rate and the neighbouring rates are rather limited.

As was noted above, when US data has been adjusted for measurement error (US 2), the estimated cost of cutting wages was very high (amounting to nearly 40% of the average annual wage). As shown in Figure 13, this has stark implications for the optimal rate of inflation, which is estimated at 5%, close to the level indicated by Wyplosz (2001). As before, differences in welfare are rather limited in the vicinity of optimal inflation, but moving from 0% inflation to the optimal rate results in substantial welfare gains, almost 4% of consumption. These decompositions are shown in Figure 14.

Finally, as noted at various points above, downward real rigidity implies that changes in the level of inflation do not affect the incidence of the rigidity. Thus, in both the case of Belgium and Finland, the optimal rate of inflation is found to be zero, since this rate minimises the costs of changing prices.

7 Conclusions

This paper examines the issue of the optimal steady state rate of inflation in the presence of downward wage rigidities. For this purpose, we modify the workhorse model of Erceg et al. (2000) by allowing for potentially asymmetric menu costs for changing household wages. Further, we use individual data on wage changes for 5 countries (US, Germany, Belgium, Portugal and Finland) to estimate the size of the menu costs using simulated method of moments. The results point to significant downward nominal rigidity in the case of the US, especially when using data corrected for measurement errors. Portugal and Germany also exhibit, to varying degrees, downward nominal rigidity, but to a notably lesser extent than the very high estimates which can be obtained for the US. For Finland we find strong evidence of downward real wage rigidity and much weaker evidence of this phenomenon in the case of Belgium.

We show that our general equilibrium heterogenous agent model is able to match pretty well the cross-sectional wage change distributions observed in the data. Once the model has been guided and disciplined by the micro evidence, we are able to compute model consistent welfare maximising steady state inflation rates for each country. We find that for the European countries considered, optimal inflation ranges from 0 (Belgium and Finland) to 2% (Portugal) with Germany occupying an intermediate position. The US results are highly sensitive to the dataset employed. With data uncorrected for measurement error, we find an optimal rate of inflation of 2%. However, using the estimates implied by the corrected data, we arrive at an optimal rate of 5%, close to the level indicated by Wyplosz (2001) in the introduction.

Appendix: Computational Aspects

Solving the wage setter's problem

We solve the wage setter's optimisation problem by means of discrete state dynamic programming (see, for example, Ljungqvist and Sargent (2004), Chapter 4). For wages we employ a grid of 151 points with a grid width of 1% (in line with the data available in the context of the IWFP) centered on the equilibrium wage rate given by the firms marginal productivity condition. We choose a compatible grid[11] of 151 points for the idiosyncratic productivity state variable q_t. The number of gridpoints for q_t is larger than would be strictly necessary in a standard problem; we chose this amount to ensure that the model is capable of generating histograms of wage changes without gaps. Taking into account the two possible values of the Bernoulli state variable that indicates the probability of menu costs, the value function is calculated over 45,602 (=151x151x2) distinct points.

We assume that the $\epsilon_t(i)$ are distributed as *iid* Laplace (double exponential), a special case of the two-sided Weibull distribution employed by Dickens et al. (2007). We approximate the AR process for idiosyncratic productivity by using the Markov chain approach of Tauchen (1986).

In order to solve the wage setter's problem, we need values for the parameters of the households' preferences and wage adjustment cost functions. In addition, the wage setters decisions also depend on aggregate macroeconomic variables (consumption, the aggregate wage rate, aggregate hours, the inflation rate and productivity growth). For the purposes of estimating the parameters using indirect inference, we take respective values for the relevant sample periods from the FRED database of the Federal Reserve Bank of St. Louis (for the US) and from the European Commission's AMECO database for European countries. Specifically, we normalise output and hours to unity. Then, with this normalisation, we calculate the aggregate wage rate from the average labour share in the data. Similarly, aggregate consumption is given by the average share of private consumption in GDP. Inflation and productivity growth are the averages calculated for the respective sample periods.

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[11] By compatible, we mean that given our grid for q_t the set of optimal wage rates which would be chosen by households in the absence of adjustment costs would be identical to the grid for wages.

In solving for the general equilibrium of the model at different inflation rates, these aggregate values are obtained from the model as explained below.

Once we have derived the wage setter's decision rule (20), the next step is to derive the stationary joint distribution of the individual state variables, $w_{t-1}(h)$ and q_t:

$$F(w_{i,t-1}, q_{i,t}) = Prob\,(w_{t-1}(h) = w_i, q_t(h) = q_i) \tag{33}$$

We compute this object using the invariant density iteration scheme outlined in Heer and Maussner (2005). Starting with an initial guess of F we update as follows. For each point on the $w * q$ joint grid (indexed by i, k), the discretised decision rule $i' = g(i, k)$ gives us the index of the optimal choice of the current wage as a function of the previous period's wage and the current value of the individual productivity shock. The transition matrix for q gives us the probability of q_{t+1} taking on each of the $(1..Ns)$ possible values on the grid, indexed by k', given a current level of q_t, indexed by k:

$$P(k', k) = Prob\,[q(h) = q_{k'} | q_t(h) = q_k] \tag{34}$$

At each iteration, denoted by j, we start from an initial value for F_{j+1} of zero. Then we update our estimate of F_{j+1} by looping over all possible values of $w(i)$, $q(k)$ and $q\,(k\prime)$ and using the discretised decision rule to calculate:

$$F_{j+1}(i', k') = F_{j+1}(i', k') + P(k', k)F_j(i, k) \tag{35}$$

We repeat this process until our estimate of F converges.

Once we have obtained this stationary distribution, we can compute the distribution of wage levels and, using the decision rule and the transition matrix, the distribution of wage changes. From the distribution of wage changes, in turn, we can calculate the moments of interest (e.g. standard deviation, percent of wage change equal to zero, percent of wage changes less than zero, etc.).

We can also aggregate over the joint stationary distribution of w and q to compute the implied aggregate wage rate consistent with eq. (14) in the main text. This is given by:

$$\bar{W} = \left[\Sigma_{i=1}^{N_w} \Sigma_{j=1}^{N_q} F_{i,j} \left(\frac{w_i}{q_j} \right)^{\frac{1}{1-\theta_w}} \right]^{1-\theta_w} \tag{36}$$

Computing the stationary equilibrium

To compute the stationary equilibrium of the model, for a given inflation rate, we iterate along the following scheme;

1. Pick a value for aggregate hours, L
2. Given this value for L, solve equations (21) to (26) to obtain aggregate values for C and W (as well as r, K, I and Y).
3. Given these aggregate variables, solve the wage setters problem as explained in the previous Section.
4. Derive the stationary distribution for w and q and compute the implied average wage rate using eq. (36).
5. Compare $\bar{W}$ with W. Choose another value for L and repeat steps (1) to (4) until convergence is achieved ($\bar{W} = W$).

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Table 1: Data Characteristics

Country	Dataset	Years	Wage measure
Finland	Industry Employers Manual Workers Association	1988-2000	Wages/hour
Germany	IAB - Institut für Arbeitsmarkt und Berufsforschung	1987-2001	Earnings
Portugal	Quadros de Pessoal	1991-2006	Wages/hour
U.S.	PSID - Panel Study of Income Dynamics	1987-1997	Wages/hour
Belgium	Social Security Records	1990-2002	Earnings

Table 2: Calibrated Model Parameters

Description	symbol	value
Intertemporal elasticity of substitution	$\frac{1}{\sigma}$	1
Inverse of labour supply elasticity	χ	1.5
Aggregators's elasticity of labour demand	$\frac{\theta_w}{1-\theta_w}$	-11
Coefficient of labour in utility function[12]	γ	0.85
Depreciation rate	δ	0.08
Discount factor (annual)	β	0.95
Capital share in production function	α	0.3
Elasticity of demand for final goods	ϵ_p	-11
Cost of changing prices	ϕ_p	45.0
AR coefficient for idiosyncratic prod. shock	ρ	0.9

Table 3: Wage Setting Parameter Estimates

	US 1	**US 2**	**DE**	**PT**	**BE**	**FI**
c_+	0.01	-	-	0.01	-	-
c_-	0.11	0.37	0.02	0.04	-	-
c_R	-	-	-	-	0.002	0.07
p	0.49	0.81	0.5	0.76	0.5	1.0
σ_ϵ	0.09	0.08	0.08	0.05	0.08	0.03

Table 4: Data: Key Moments of Wage Change Distribution

Statistics	**US 1**	**US 2**	**DE**	**PT**	**BE**	**FI**
Mean	0.040	0.039	0.036	0.051	0.045	0.037
Std.Dev	0.075	0.061	0.044	0.058	0.054	0.03
% zero	0.157	0.265	0.076	0.139	0.006	0.01
% <0	0.160	0.069	0.141	0.050	0.098	0.03
Mean (dw>0)	0.072	0.069	0.050	0.068	0.056	0.04
Mean (dw<0)	-0.074	-0.087	-0.034	-0.081	-0.050	-0.04
DRWR	-	-	-	-	0.593	-
%<inf	-	-	-	-	-	0.05
Sample	88-97	88-97	88-01	92-06	91-02	00

Table 5: Model: Key Moments of Wage Change Distribution

Statistics	**US 1**	**US 2**	**DE**	**PT**	**BE**	**FI**
Mean	0.040	0.039	0.036	0.051	0.045	0.037
Std.Dev	0.08	0.07	0.05	0.04	0.07	0.03
% zero	0.16	0.26	0.10	0.15	0.04	0.00
% <0	0.16	0.07	0.17	0.15	0.21	0.05
Mean (dw>0)	0.075	0.068	0.05	0.05	0.04	0.04
Mean (dw<0)	-0.073	-0.087	-0.047	-0.05	-0.050	-0.03
DRWR	-	-	-	-	0.63	-
%<inf	-	-	-	-	-	0.05

Table 6: List of Variables

Y	Output	L	Hours Worked
C	Consumption	$q_t(h)$	Idiosync Prod. shock
I	Investment	p_t	price level
Z	Government Spending	R	Interest Rate
K	Capital Stock	W	Wage Rate

Figure 1: Wage Change Histograms: Data vs Model (a)

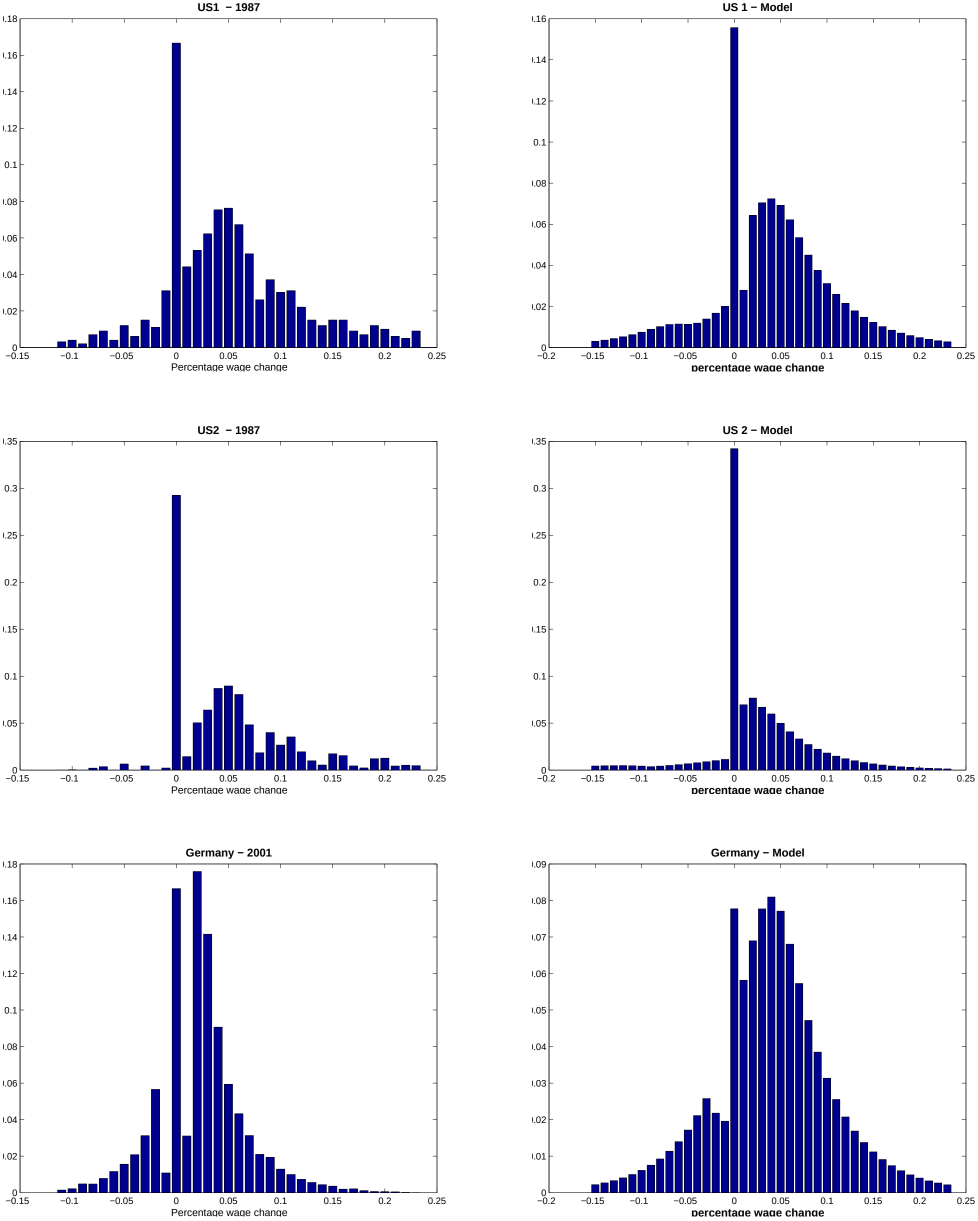


Figure 2: Wage Change Histograms: Data vs Model (b)

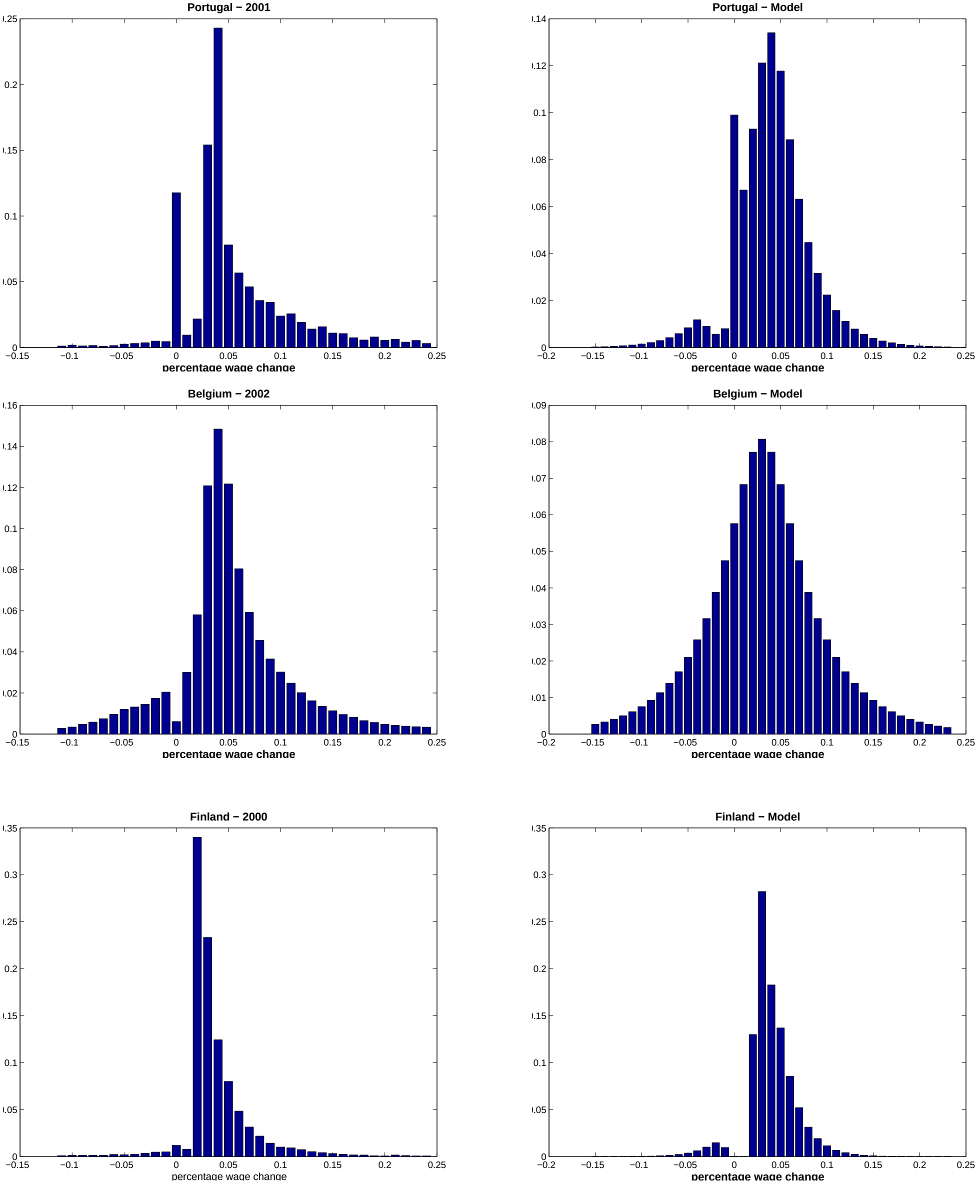


Figure 3: Decision Rules for the Household

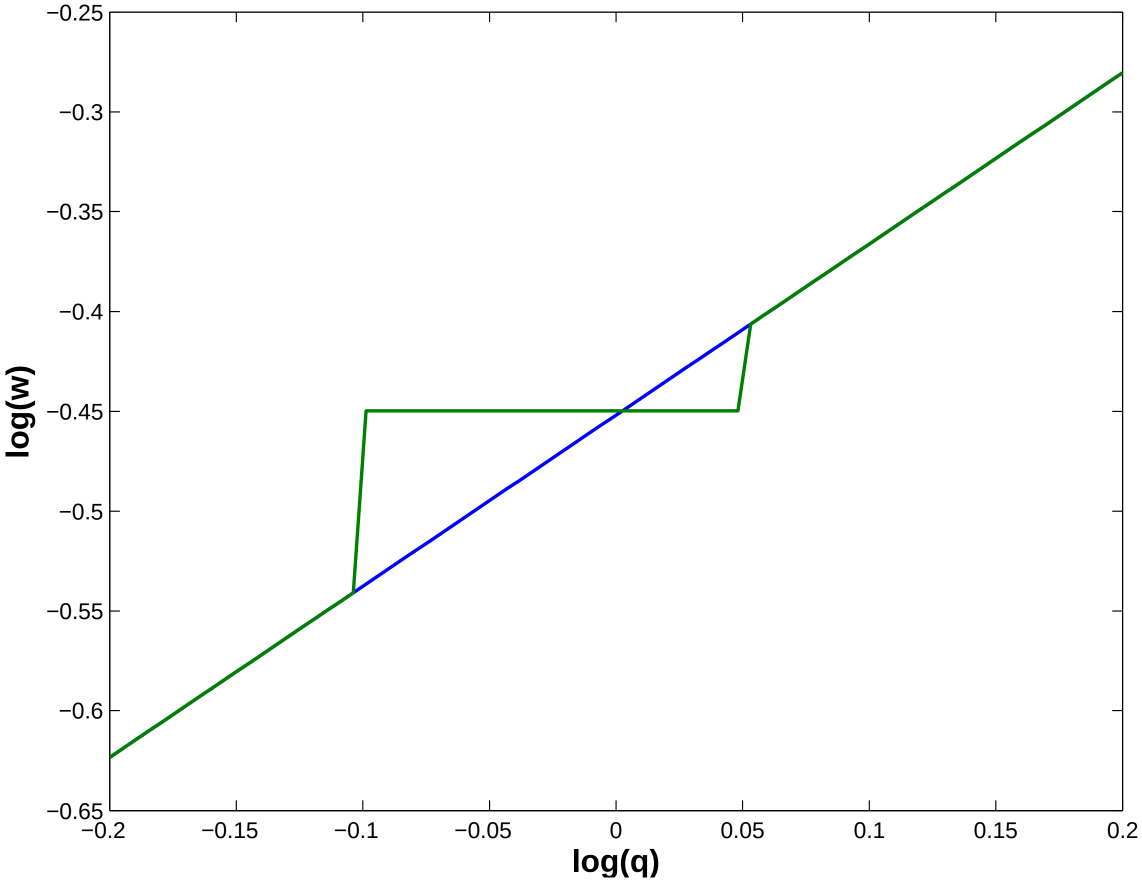


Figure 4: Determination of the General Equilibrium

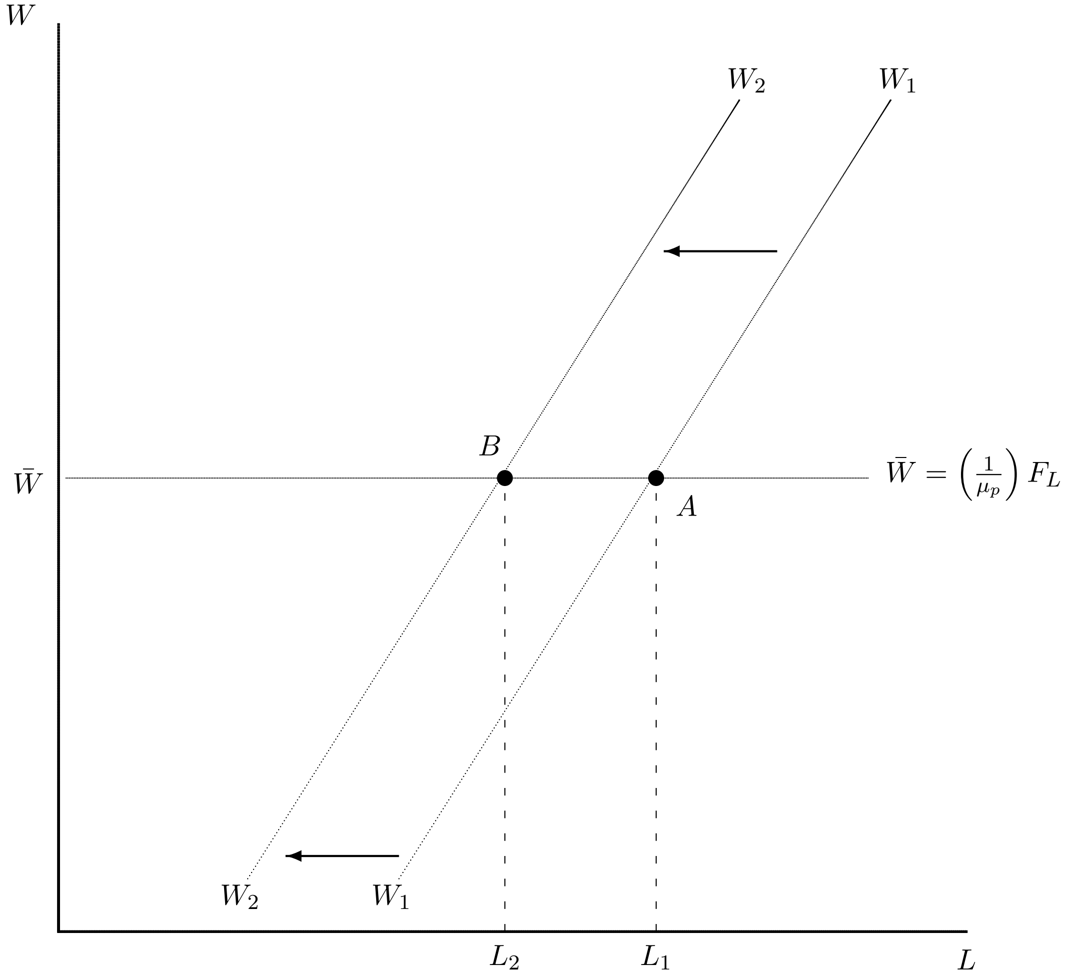


Figure 5: Inflation and Welfare - No Wage Adjustment Costs

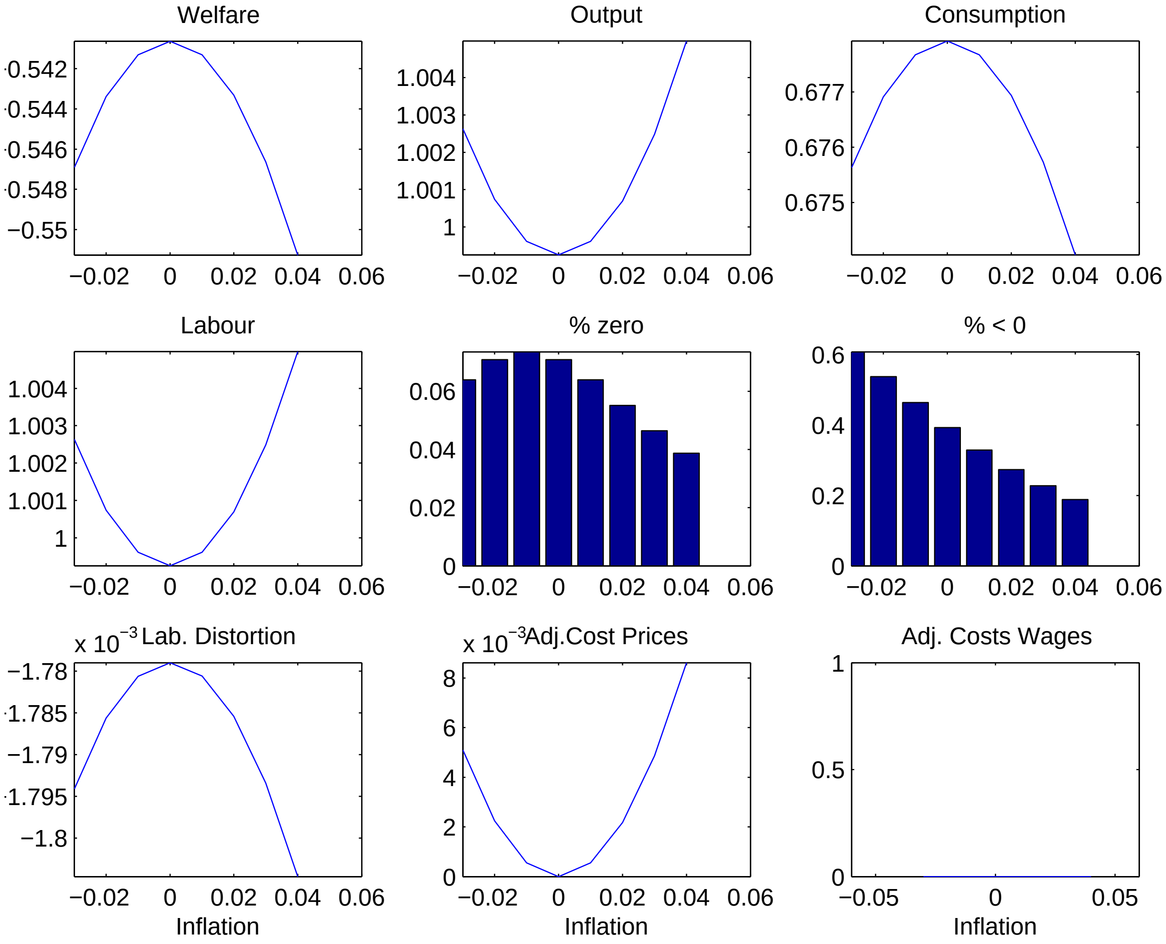


Figure 6: Inflation and Welfare - Real Wage Adjustment Costs Only

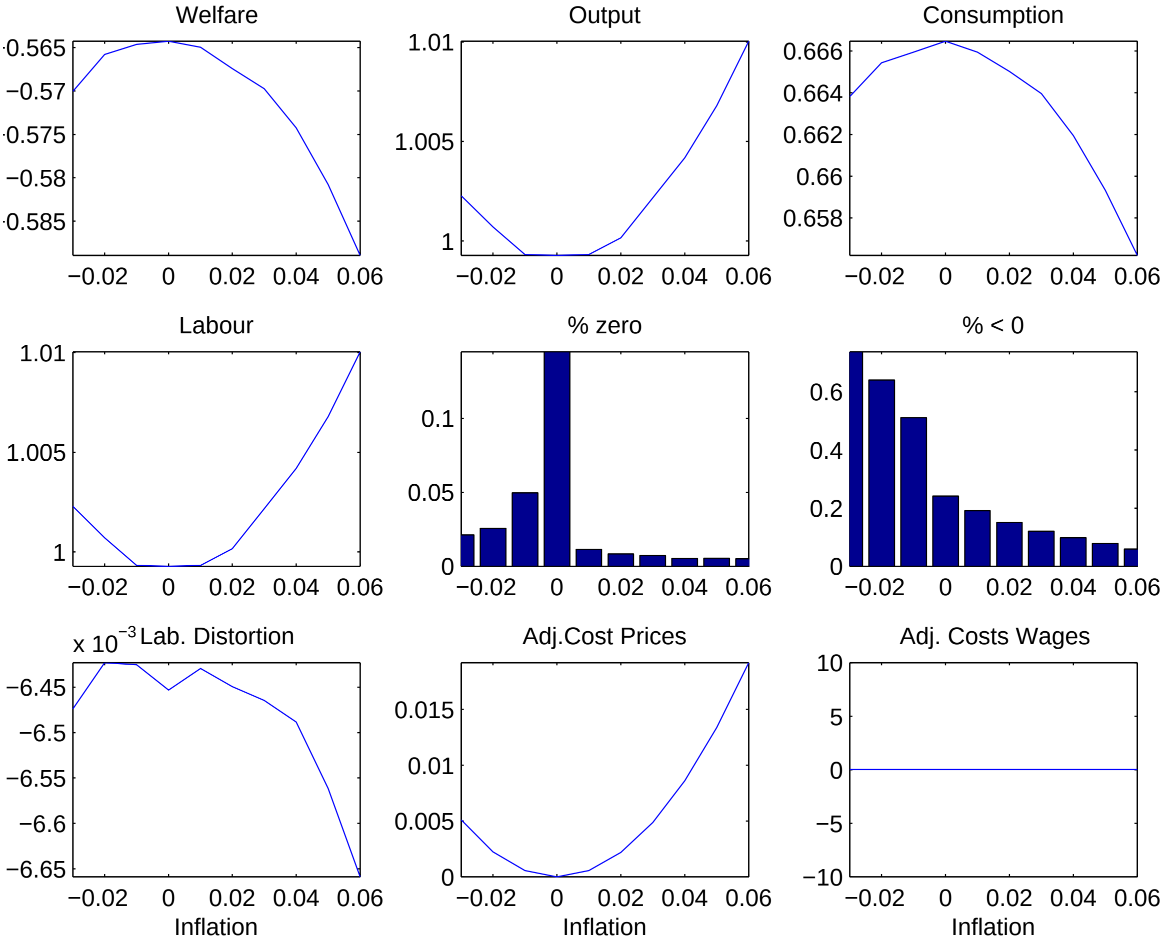


Figure 7: Inflation and Welfare - US 1

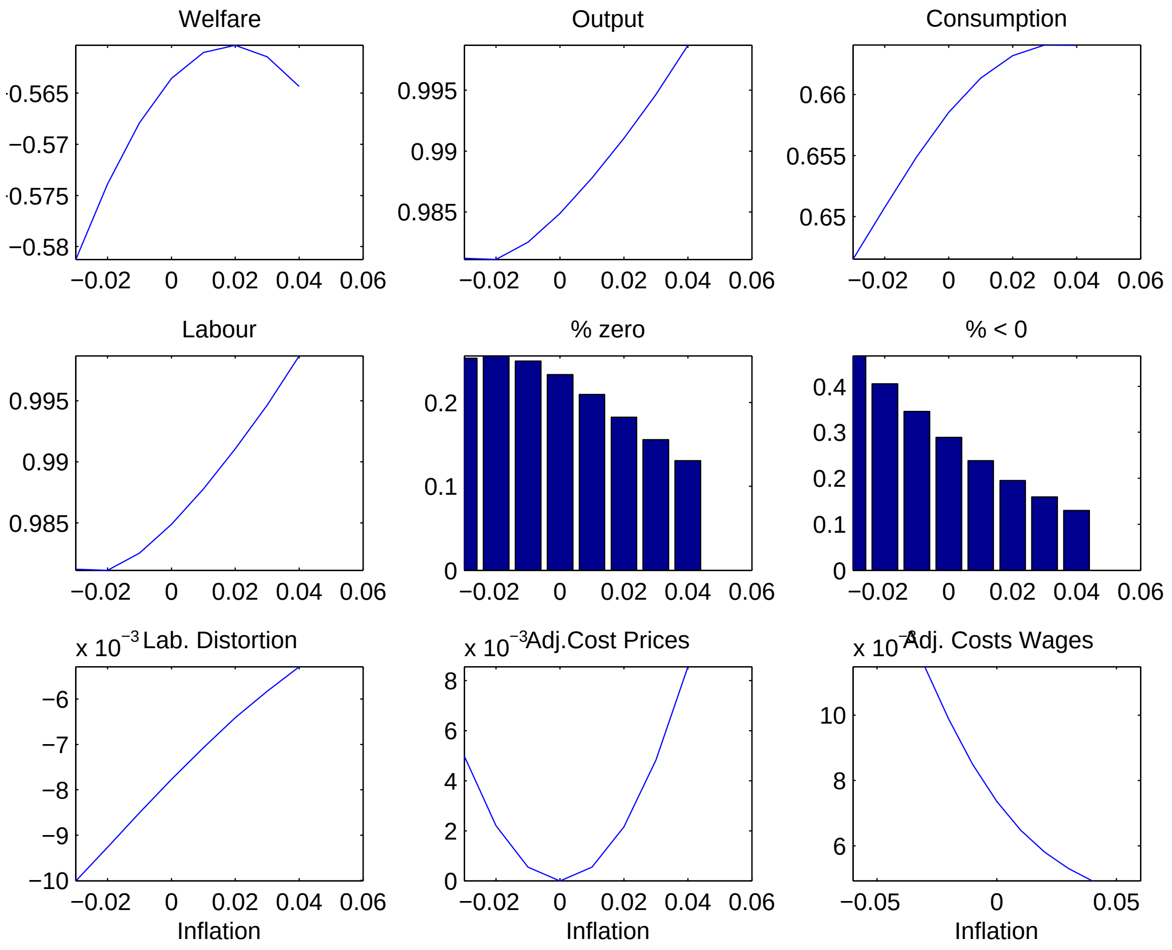


Figure 8: Decomposition of the Change in Welfare - US 1

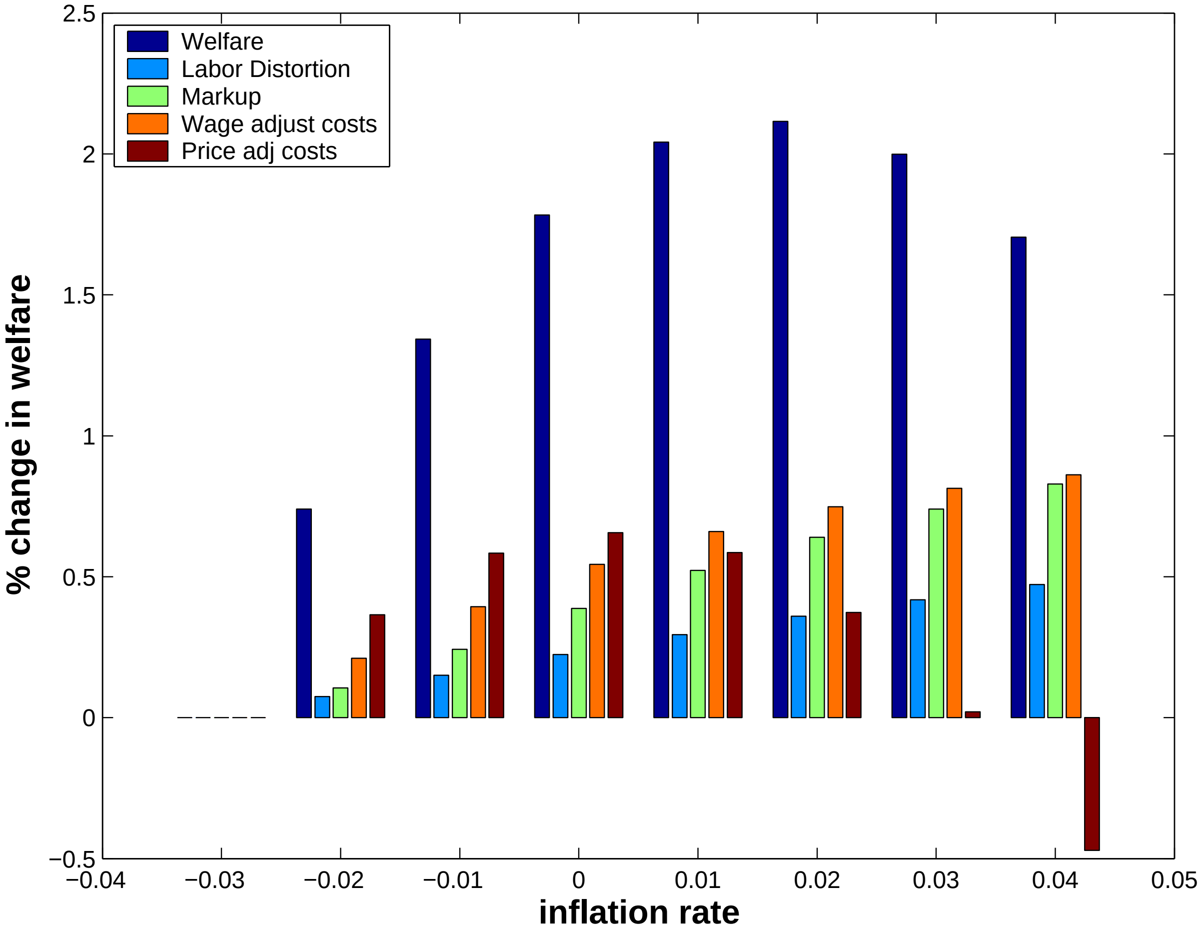


Figure 9: Inflation and Welfare - Portugal

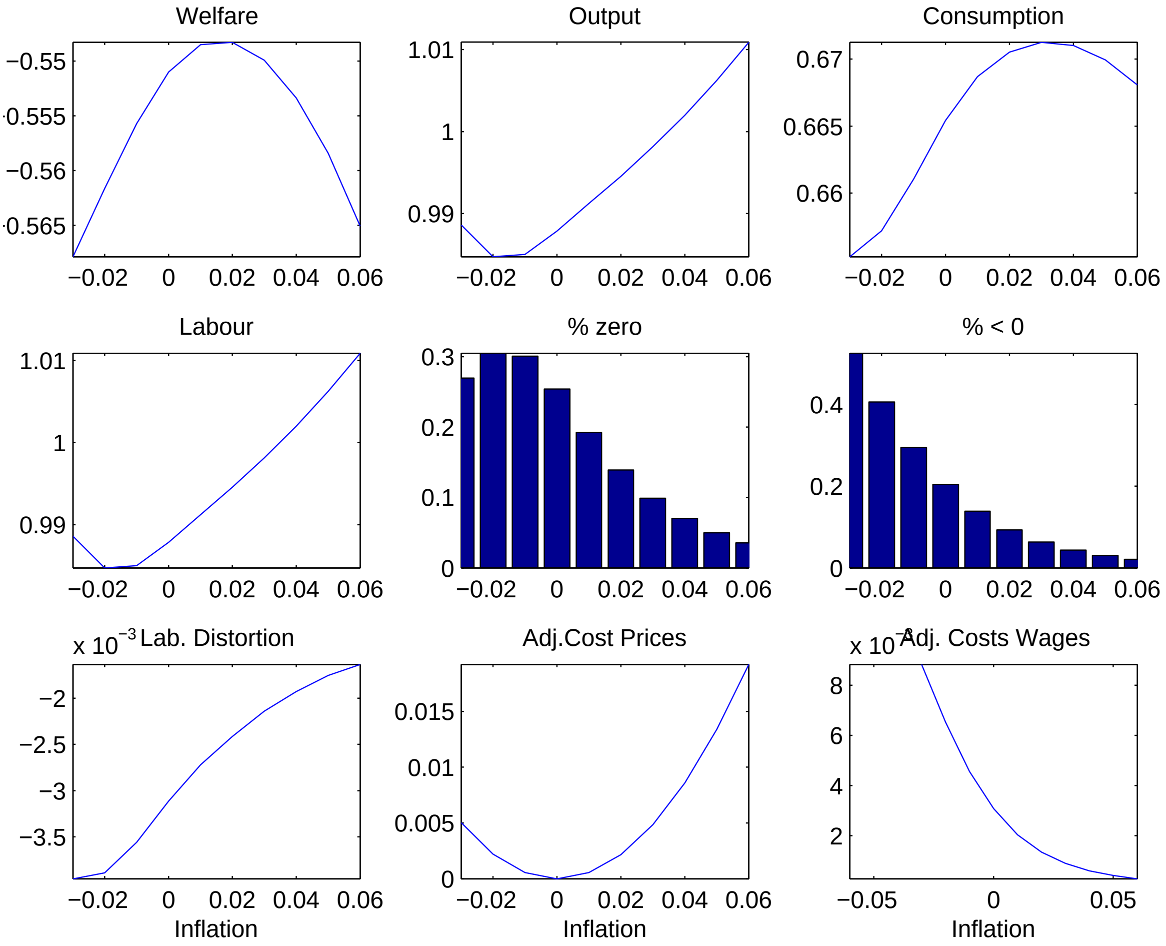


Figure 10: Decomposition of the Change in Welfare - PT

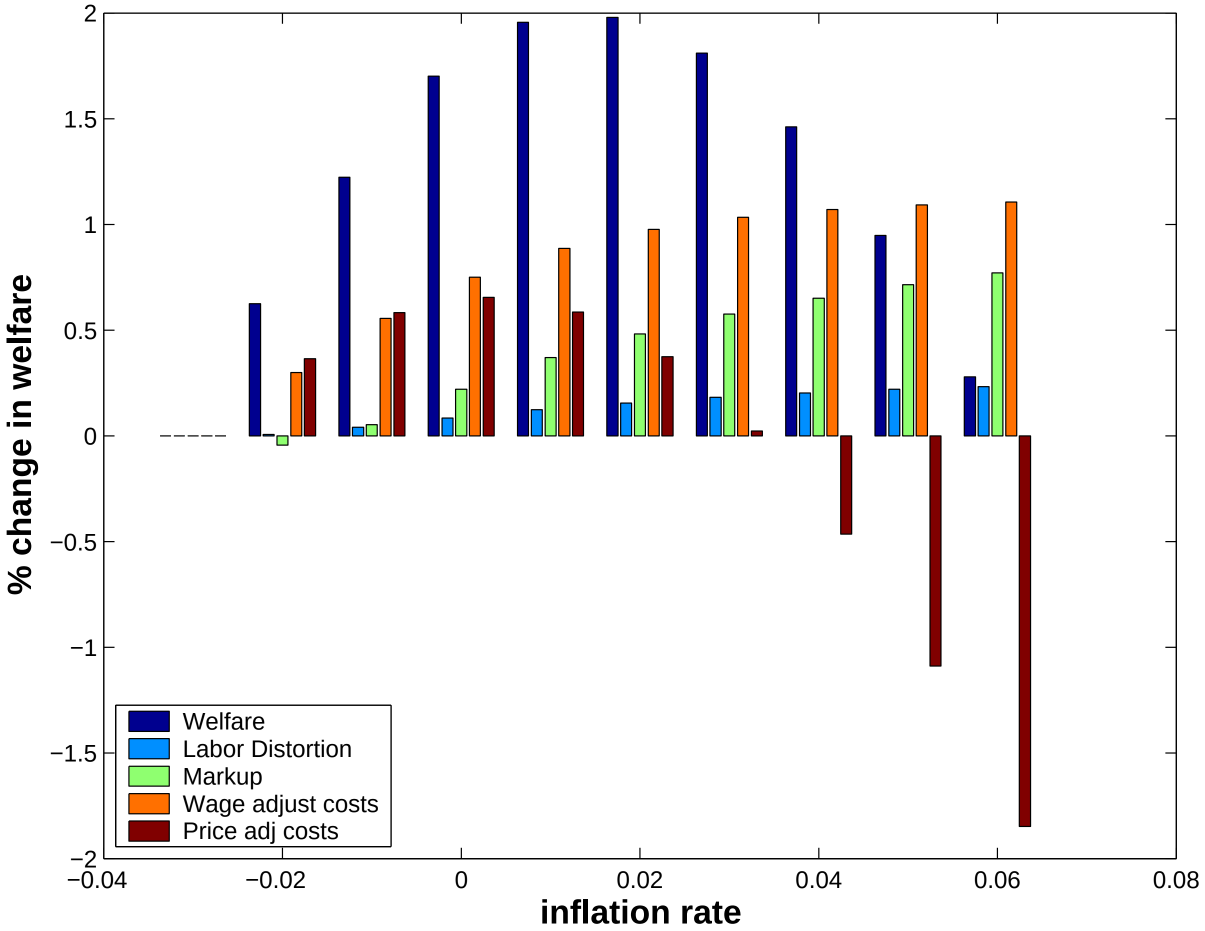


Figure 11: Inflation and Welfare - Germany

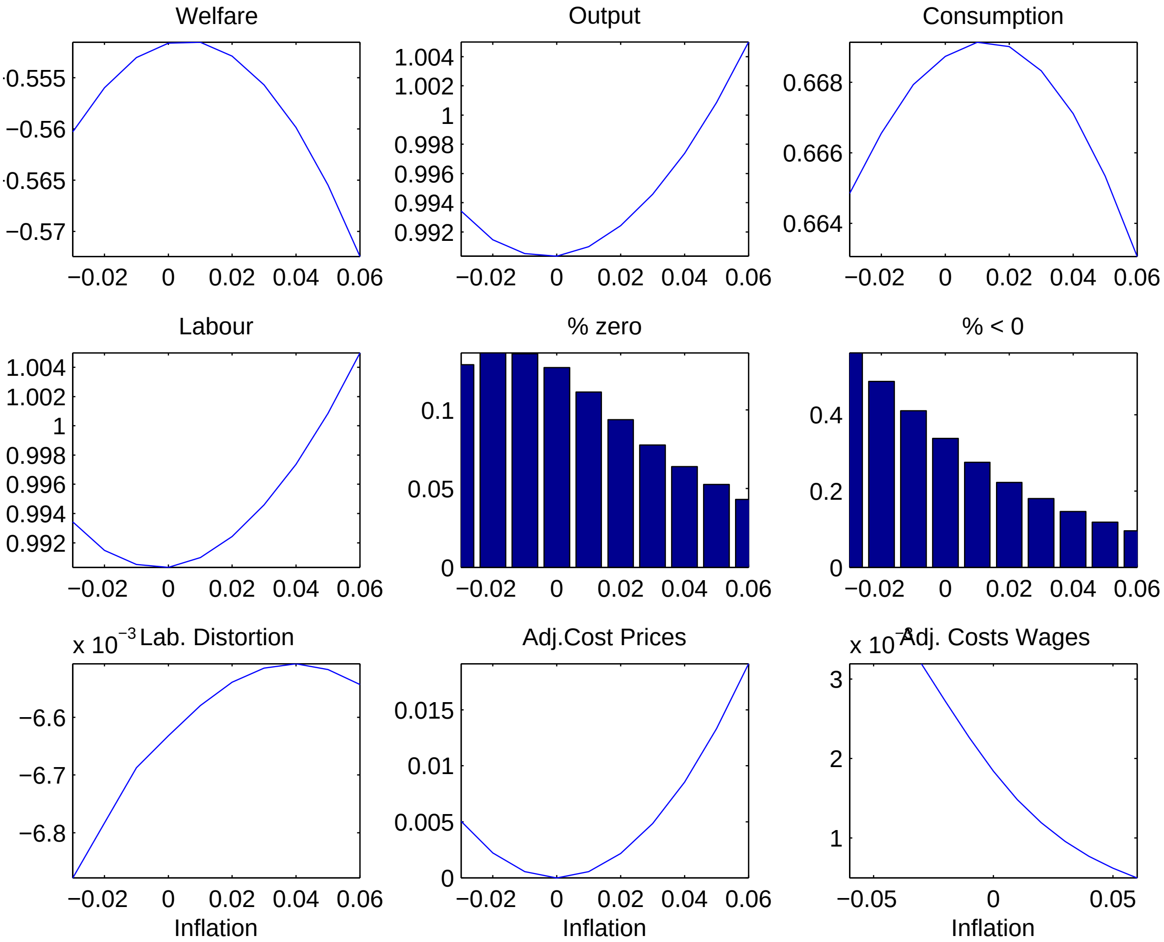


Figure 12: Decomposition of the Change in Welfare - DE

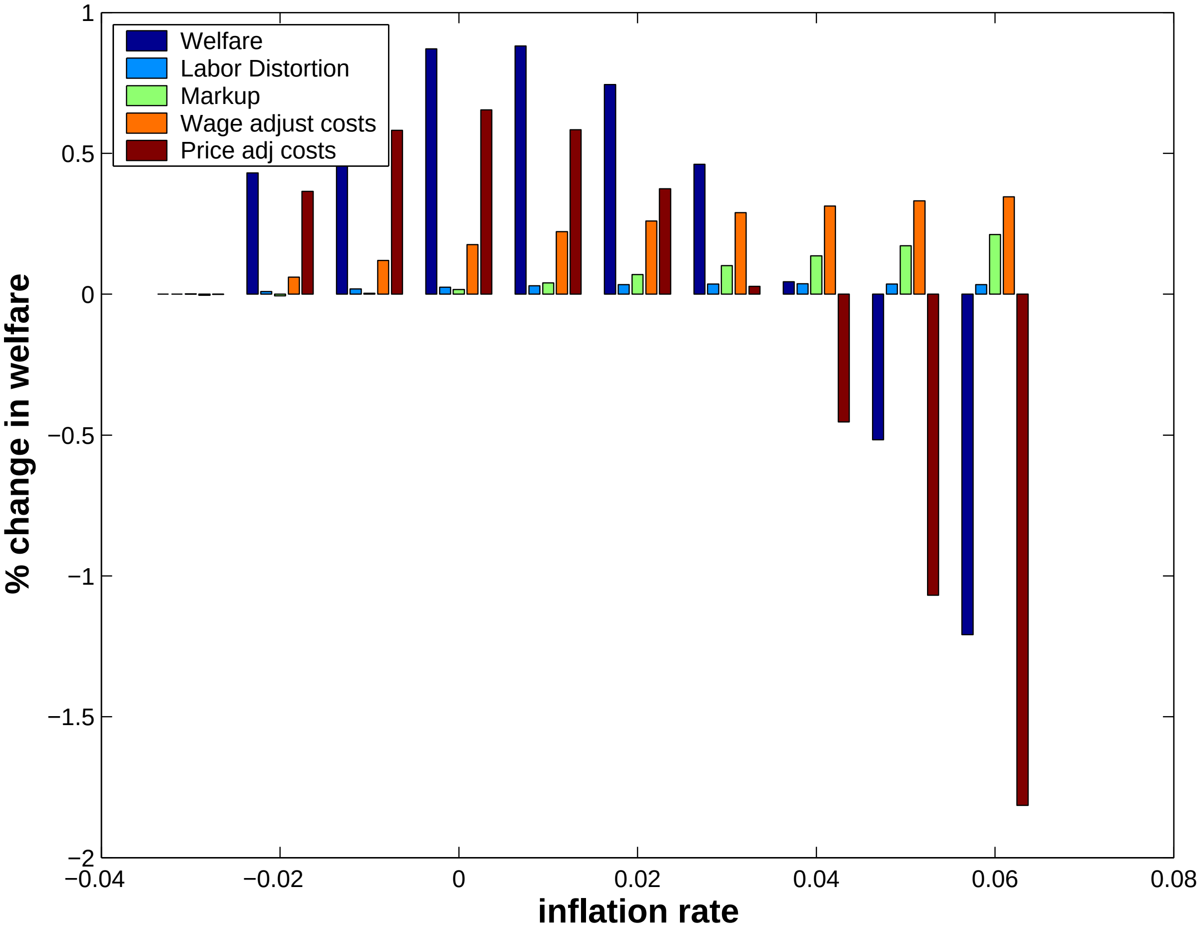


Figure 13: Inflation and Welfare - US 2

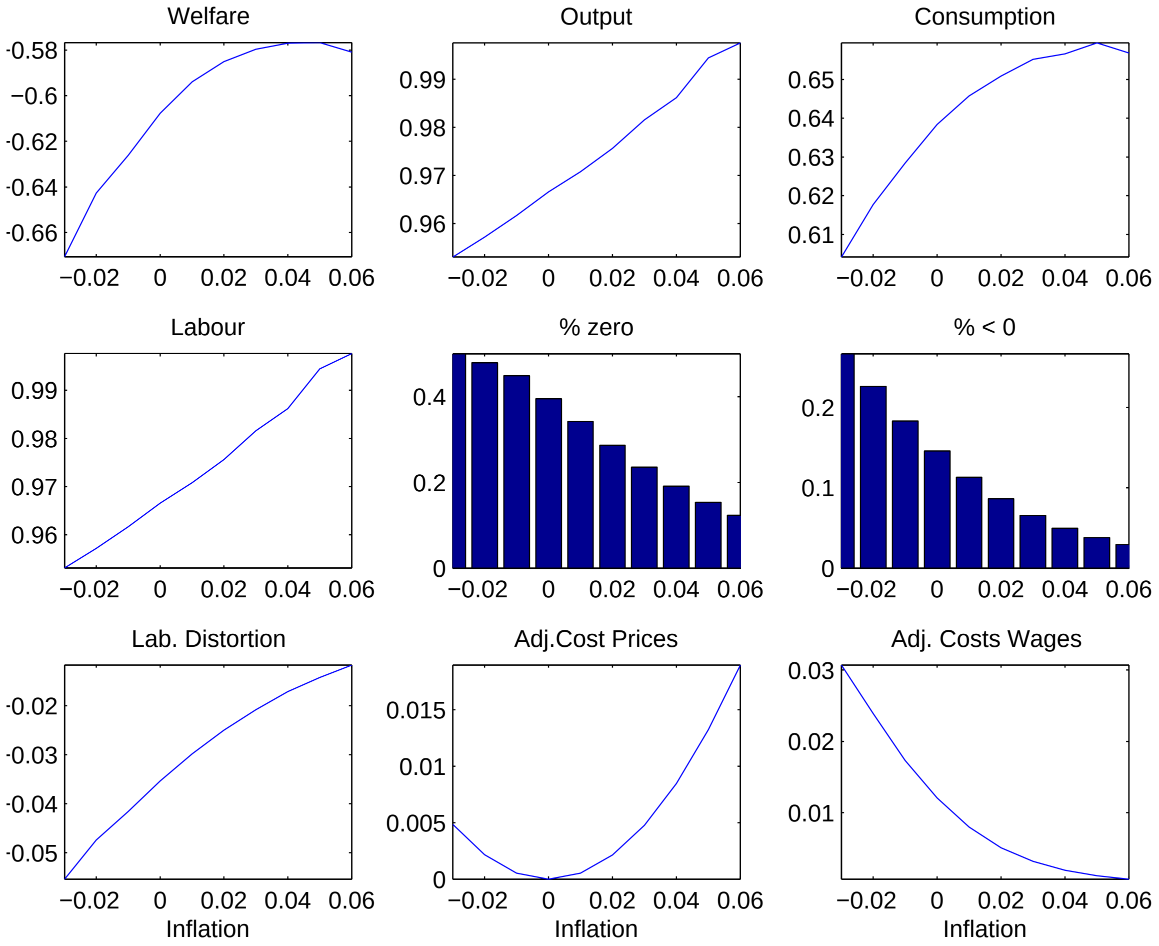
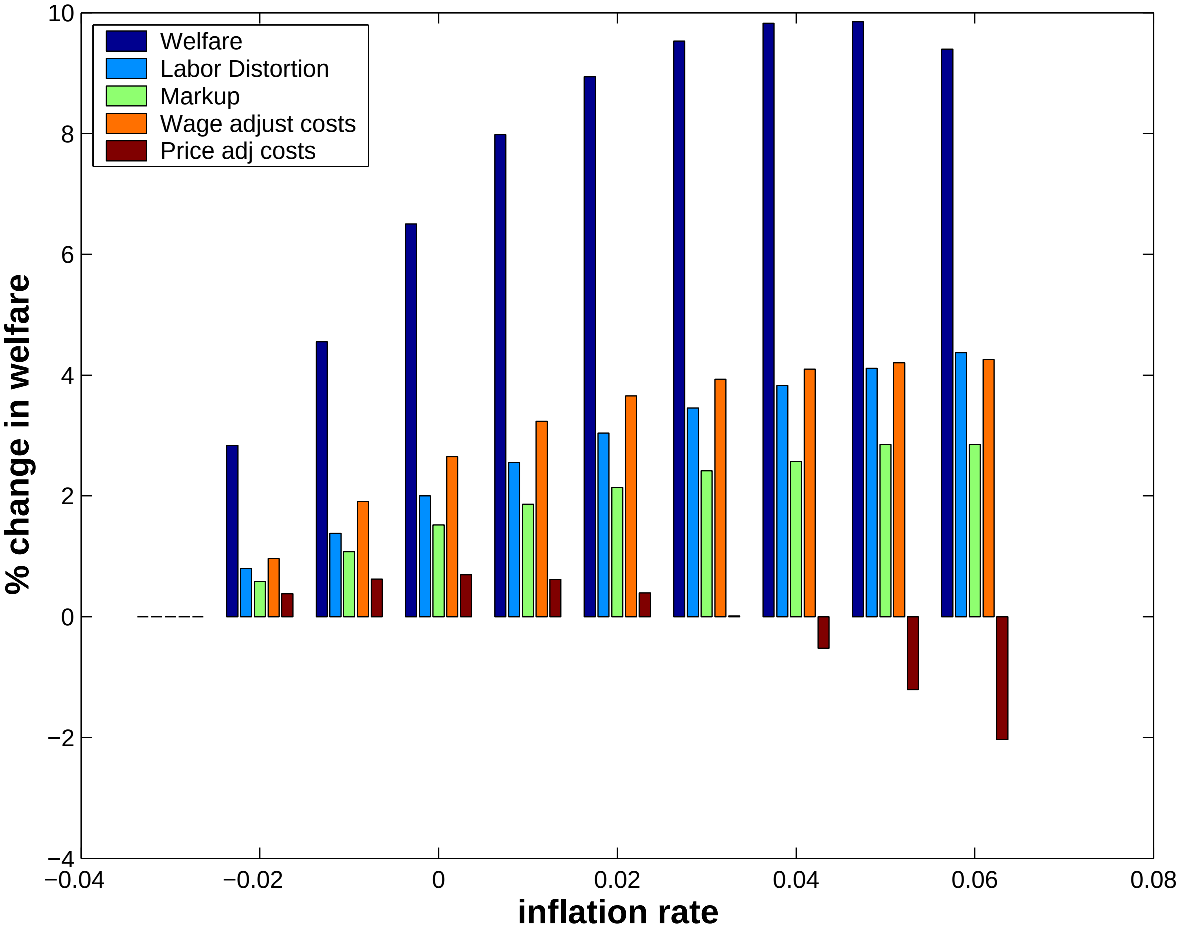


Figure 14: Decomposition of the Change in Welfare - US 2



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