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U.S. wage-price dynamics, before, during and after COVID-19, through the lens of an empirical econometric model.*

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Abstract

We specify an empirical model of US inflation which has the dynamics of wage and price setting at its core. In the dynamic wage equation an equilibrium-correction term connects the wage level to industrial prosperity indicators. In that way, the role of wage setting in the dynamics of the functional income distribution and in the rent-sharing processes becomes clearer than with a wage Phillips curve. At the same time, it does not exclude such explanatory variables that are typically found in empirical U.S. wage Phillips curves: changes in costs-of-living and indicators of labour market tightness, On the price side of the wage-price spiral, the empirical model includes an import price index and the price of oil. Existing studies of pandemic-era inflation have confirmed that shocks to energy prices were important, but have not included imported inflation more broadly. Estimation and simulation results indicate that wage growth was strongly affected early in the pandemic, but without breaking the long-run mean of wage growth. The strong rise in the price index of private consumption expenditure that started in 2021 therefore had a background in an increased wage level, but was dependent on other factors to evolve as it did: Namely a strong and broad increase in international prices, and in energy prices in particular.

1 Introduction

Even while COVID-19 was still a threat to public health and to the stability of national economies, price levels in many countries started to increase faster than had been usual since the 1990s. USA is a particularly interesting case, since it is easy to imagine that the

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policy response to U.S. inflation also influence monetary policy decisions elsewhere in the world.

We build a multi-equation econometric model to analyze the causes of the higher inflation in the U.S.. We also investigate whether there has been a structural break in the data-generating process after COVID-19, which requires that we first establish a model based on a long, pre COVID-19, data set. In our model, the typical U.S. wage-Phillips curve is replaced by a wage growth equation with a rent-sharing term as one of the explanatory variables. In that way, the model captures that inflation is integrated in the process that determined functional income distribution. Another feature of the model is a non-linear wage response to the rate of unemployment.

Unquestionably, higher prices of natural gas and electricity were important drivers of inflation already before the Russian invasion of Ukraine. Our model includes these factors trough import price inflation. However, it is plausible that a strong bounce back in aggregate demand, together with pandemic related frictions in product and labour markets, also contributed to higher inflation through a domestic wage-price spiral, which therefore forms the centrepiece of our model.

Conceptually, the wage-price spiral captures the idea of a positive feedback process between product prices and wage compensation, see Blanchard (1987). Firms try to use mark-up pricing as a way to compensate for raised (variable) costs of production. They are also likely to succeed in this, to a degree that may depend on structural aspects of demand (eg., price elasticities) and on the market form (monopolistic competition). On the worker side, one goal in individual pay negotiations, as well as in collective wage bargaining processes, is to seek compensation for increased costs of living. However, whether the degree of compensation is complete or partial can depend on both market forces and on institutions. These are examples of related questions that invite empirical modelling as an approach to co-explanation.

Recent pandemic-era motivated theoretical developments have focused on the role that scare non-labour inputs can initially have on the general price level, and the subsequent wage-response. In a New Keynesian model with wage-price spirals developed by Lorenzoni and Werning (2023), excess demand may force a sharp rise in the prices of scarce non-labour inputs and lead to an increase in price inflation. The implication of the paper is however that the wage gains that followed the initial surge in prices need not inevitably lead to wages and prices spiralling out of control.

There are already several other model-based empirical explanations inflation in the pandemic era. Cecchetti et al. (2023) combine historical evidence (from the 1950s and onward) and inflation modelling to analyse periods of disinflation, including the post pandemic one. Their preferred price Phillips curve model is a non-linear function of a labour market tightness indicator (the rate of unemployment in the simplest case). It indicates that a hot and tightening labour market raises inflation, but slackening of an already cold labour market does not lower inflation. The econometric results show that the choice of sample period is important for the model's ability to explain the pandemic era inflation. Models estimated using data that include the high and volatile inflation episodes of the 1960s and 1970s seem to do a better job of tracking the new rise in inflation, than models that are based on the Great moderation. This is consistent with other results that indicate a flatting of the Phillips curve during the Great moderation, see Blanchard (2016)) and Hazel et al. (2022). However, the Phillips curve oriented literature also indicate that the curve may have become steeper again when data from the pandemic era is taken into account Ari et al. (2023).

The instability of the U.S. Phillips curve was recognized long before COVID-19, see Del Negro et al. (2020) and the references therein. However, finding that the coefficient of the rate of unemployment, U, in a simple model of wage inflation Δw_t is unstable, does not imply that the slope coefficient of U is unstable in a larger model. Castle and Hendry (2023) find that for a long historical sample of UK inflation, U has a stable negative slope coefficient in regression models that include all relevant explanatory variables.

From the wage-curve branch of the literature, Blanchflower et al. (2024) find empirically that the unemployment rate is not key to explaining wage growth data in the USA since the Great recession. Using panel data, they provide evidence supporting that other indicators of labour market pressure are more relevant: the non-employment rate, the under-employment rate and the inactivity rate.

Blanchard and Bernanke (2023) give a comprehensive analysis of inflation in the pandemic era anchored in a model where short- and long-term inflation expectations together with labour market tightness are the main drivers. Their analysis indicates that wage increases and a tight labour market made modest contributions to inflation early in the pandemic. However, latent demand that was let free when the pandemic ended, raised the price level given wages by increasing the demand for goods for which supply was inelastic. Energy prices alone accounted for much of the rise in overall inflation in late 2021 and first half of 2022.

The contribution by Ball et al. (2022) had concluded that the increase in headline inflation resulted primary from shocks to food and energy prices, but that labour market tightness had been an important factor of core inflation. Blanchard and Bernanke's empirical results do not contradict this, but their analysis was more detailed and was based on a multiple equation model of price and wage dynamics. In their final assessment, Blanchard and Bernanke (2023) were generally more optimistic than Ball et al. (2022) about the cost of disinflation.

On the role of fiscal stimulus in building up latent demand pressure, Hagedorn (2023) gives theoretical arguments for inclusion of the change in federal transfers in a nominal demand augmented price Phillips curve based on the theory of state dependent pricing, and reports empirical results which support that hypothesis.

In our offering we develop an empirical multiple-equation model which is guided by a theoretical model of the wage-price spiral. In this respect the paper by Blanchard and Bernanke is closest to ours. However, there are differences in econometric method, variables and sample period. Our model is not tailored for the pandemic era, and we are interested in the explanatory power of models that are relevant over a longer sample period, going back to the mid-1960s using quarterly data.

As mentioned, the hypothesis that COVID-19 caused structural breaks in the Phillips curve has been addressed in the existing studies, with mixed results. After testing, we include a number of breaks in the deterministic terms in the model equations. We do not find any significant breaks after first quarter of 2020. Conditional on the breaks, the slope coefficients of the variables in the model equations are relatively stable over time. That result includes the slope of the labour market tightness variable in the wage inflation, which is non-linear in the rate of unemployment.

In the U.S., there is a tradition for empirical models that have Phillips curves at the core. In our investigation we use more general model equations, based on cointegration and equilibrium correction models (EqCM). In this we build on Bårdsen and Nymoen (2009) where we modelled annual time series of US wage and price indices. However, the insight that EqCM formulations can be an improvement on Phillips curve models of wage-price inflation is much older, e.g., Sargan (1980).

The EqCM-approach to wage modelling, it is also well suited to test empirically the role of variables from the functional income distribution in the inflation process. Such factors, e.g., the lagged wage share, are omitted from the standard PCM-approach, which may be reasonable given that collective bargaining have come to play a minor role in the wage setting process in the U.S.. However, it is possible that workers can earn a share of non-competitive rents also in a system of non-unionised wage setting. If rent-sharing is a phenomenon of any importance, it may be picked up by estimation of EqCM-wage equations. However, the approach does not rule out finding a traditional U.S. Phillips curve empirically, as it is a special case.

Regarding inflation in the pandemic era, our modelling results give an explanation summarized in the points below.

(i) As the effects of the financial crisis (and ensuing income and job crises) had been overcome, nominal wage growth had become higher, and more stable, than for a long time. As consumer prices grew less than wages, the purchasing power increased over the period from 2017(1) to 2019(4). This was coinciding with a steady reduction in the rate of unemployment, which together with other indicators like vacancies indicated a labour market tightening. However, average labour productivity growth was also positive during this period, which (in accordance with our model) must have mitigated the inflationary effects of a hotter labour market. The effects of the 50 percent reduction in the oil price in 2015, and the resulting fall in overall import prices, can be seen as contributing in the same direction.

(ii) Because of the lockdown measures taken to protect public health, the rate of unemployment increased from 3.8 percent in 2019(4) to 13 percent in 2020(1). This did not affect immediately the growth in wages (compensation to workers), but by 2020(2) that rate had jumped to 10 percent (annual change). However, labour productivity increased markedly in the same period, so this was in large part a composition effect, that did not let loose a wage-price spiral. Overall inflation stayed below 2 percent (annual change) during 2020, and that was the case for the change in the GDP deflator as well.

(iii) In 2021(1) wage growth had already adjusted back to pre-pandemic values, and the increase in inflation of that year was largely driven by developments in goods markets, that is from increases in prices given wages. In our model, this development is captured by the increase in the prices of imports and in energy prices (represented by the price of oil). We also estimate a separate effect of the huge government transfers early in the pandemic, as suggested by Hagedorn (2023). As we have an aggregate model, we are not able to represent the shifts in composition of demand (e.g., from services to durable goods) during the pandemic that existing studies has highlighted, e.g., Guerrieri et al. (2023). However, as a part of that change in demand was met by imports, it is not unreasonable to think that it is picked up by imported inflation in our model (at least in part).

(iv) The price shock of 2021 was huge, and with a generic wage-price spiral, our model attributes an important part of the inflation in 2022 and 2023 to the persistent effects of the price shocks in 2021. However, import price growth continued to be high in the first half of 2022, before starting to drop off markedly during the the two last quarters of 2022 and into 2023. It can be noted that import price growth is endogenous in our model, unlike in the models cited above.

Existing studies of pandemic-era inflation have confirmed that shocks to energy prices were important, but have not included imported inflation like we do. The mentioned work by Blanchard and Bernanke is an example. There may be good reasons for this modelling choice, for example that the U.S. economy is so huge that it is the internal wage-price transmissions that dominate the picture. On the other hand, the US economy is fully integrated with the global economy and it is difficult to think that the US was insulated from the disruptions during the pandemic (and after) that affected the price of nearly all tradables.

The organization of the rest of the paper is as follows. We start with the analytical framework for the interacting dynamics of wage and price setting in Section 2. It encompasses traditional Phillips curves, New Keynesian Phillips curves, and equilibrium correction models, which all imply their own specific restrictions on a cointegrated VAR. We then clarify the main decisions taken about operational variable definitions, and the main steps in empirical implementation of the model (section 3). In Section 4 we use the empirical model to simulate US wage-price dynamics, before during and (so far) after COVID-19, substantiating (we hope) the story told in sections (i)-(iv) immediately above. In section 5 we give a brief summary, and a few thoughts on improvements, robustifications and extensions of this work.

2 A theoretical framework

There are several approaches that can be used to put the idea about joint and dynamic dependencies between wages and prices on model form. Our method in this paper goes back to the error-correction models that Denis Sargan formulated early in the history of econometric modelling of wages and prices, see eg., Sargan (1964, 1980). During the 1990s, the econometrics of co-integrated variables was developed in ways that (among other things) allowed long-run relationships containing real-wages to be included as attractors in models of changes in wages and prices that belong to the class of equilibrium correction models, EqCMs, cf. Bårdsen et al. (2005, Ch. 5).[1][2]

[1]Hendry (1995, ch. 7.10) made the point that the defining characteristic of EqCM dynamics is that it adjusts towards an equilibrium implied by the stability of the (homogeneous part) of the model equation, and to use the acronym EqCM for equilibrium-correction model instead than for error-correction model. We follow Hendry's convention.

[2]EqCM-type wage and price models are also known as incomplete competition models, since they are seen as consistent with the idea that firms typically have some marked power in product markets (monopolistic competition is a special case). Possibly also in wage setting, but then often in a bargaining context, with workers or their union, as the opposite part.

In the U.S., there is a strong tradition for using Phillips curve models, PCMs, in econometric inflation modelling, cf. Gordon (1997, 1998); Blanchard (2016). However, the difference between the two modelling traditions is not as large as it is sometimes made out to be, at least conceptually. As pointed out in Bårdsen and Nymoen (2003, 2009), both EqCMs and PCMs imply dynamics that are equilibrium correcting.

With wage-price EqCM equations, wages adjust with respect to lagged deviations between the real wage and a target real wage. As shown by Forslund et al. (2008), theories of wage bargaining between strong parties imply EqCM dynamics where the target is the labour share of value added, which clarifies the role of wage setting in the process that generate the functional income distribution.

When the wage- and price spiral is specified with PCM equations, equilibrium correction takes place indirectly, through adjustment of the rate of unemployment, which implies natural rate dynamics as a particular special case of equilibrium correction.

Collective bargaining as found in several European countries may give rise to (explicit) equilibrium-correction dynamics. However, a related concept is rent-sharing, and evidence suggests that also non-union workers earn so called non-competitive rents, Carruth and Oswald (1989, Ch. 3), Blanchflower et al. (1996).

As has been pointed out by Pencavel (1985) and others, wage setting models with unions as economic agents with real wage targets, may have a wider relevance than might be first apparent, and it may be appropriate to imagine wage setting as the outcome of a process of implicit bargaining. Such a framework encompasses both strong and weaker versions of the relationship between compensation and profitability, Nymoen (2021).

It is worth keeping in mind that the functional income distribution is connected to the wage setting process. The current state of the distribution can be a factor in wage formation, and the evolution of the distribution of value added between workers and capital owners is to a large extent result of wage settlements.

We next give a framework which encompasses EqCM and PCM type wage-price models. In section 2.4 below we discuss how, subject to mild assumptions, the framework also encompasses wage-price dynamics implied by New Keynesian Phillips curves.

2.1 Wage-price dynamics

In the following, lower-case letters denote the natural logarithm of upper-case variable names, i.e. $x_t \equiv ln(X_t)$.We let q denote the aggregate product price, w the wage level and p the consumer price price index. An import price index, pi, is also relevant to include in a model for wage-price dynamics, as goods are imported to the US both for direct consumption and use as input in production. The main real variables in the stylized model are the unemployment rate, u and labour productivity (eg., output per hour), denoted by z. At the outset it is convenient to think of all variables as measured in logs. However, in the empirical model care must be taken when it comes to the rate of unemployment, since modellers of US data often have decided to use a Phillips-curve which is linear in the rate of unemployment, but with breaks ("flattening" and "steepening" of wage and price Phillips-curves).

The core of the model can be written as a pair of equations for wage and price setting in simultaneous equations model (SEM) form:

$$\Delta w_t = c_w + \psi_{wq}\Delta q_t + \psi_{wz}\Delta z_t + \psi_{wp}\Delta p_t - \mu_w\, u_{t-1} \\ - \theta_w \left[(w_{t-1} - q_{t-1} - \iota\, z_{t-1}) + \omega(p_{t-1} - q_{t-1})\right] + \varepsilon_{w,t}. \tag{1}$$

$$\Delta q_t = c_q + \psi_{qw}\,\Delta w_t + \psi_{qpi}\Delta pi_t + \psi_{qz}\,\Delta z_t - \mu_q u_{t-1} \\ - \theta_q\,(q_{t-1} - w_{t-1} + z_{t-1}) + \varepsilon_{q,t}, \tag{2}$$

where Δ is the difference operator, e.g., $\Delta w_t \equiv w_t - w_{t-1}$, all coefficients are defined as non-negative, and the two error terms ε_{wt} and ε_{qt} may be assumed to be uncorrelated, in analogy with structural shocks.[3] The use of the notation:

$$\mu_w = \theta_w\varpi + \varphi \tag{3}$$

$$\mu_q = \theta_q\vartheta + \varsigma \tag{4}$$

for the two coefficients of u_{t-1} means that the Phillips curve model, PCM, and the wage-price equilibrium correction model, WP-EqCM, are both encompassed by the framework (see immediately below). It goes almost without saying that in empirical applications, different measures of labour market and capacity utilisation can be used in the two equations. The use of u_{t-1} however is fitting for a stylized model.

It is also useful to define a relationship that mimics how the consumer price index p, weighs together the price of US production q, and the price of imports pi:

$$p_t = \phi q_t + (1-\phi)pi_t,\ 0 < \phi < 1. \tag{5}$$

By the use of (5) and the differenced version:

$$\Delta p_t = \phi\Delta q_t + (1-\phi)\Delta pi_t,\ 0 < \phi < 1. \tag{6}$$

Δp_t and p_t can be eliminated from (1)-(2) by substitution, and the model can be solved for wages, w_t, and producer prices, q_t.[4]

2.2 Two models: WP-EqCM and PCM

With the above framework, the WP-EqCM can be defined by the following constraints:

$$\text{WP-EqCM: } \theta_w,\theta_q > 0 \ \text{ and } \ \mu_w = \theta_w\varpi\ ,\ \mu_q = \theta_q\vartheta, \tag{7}$$

and the PCM can be defined by the constraints:

$$\text{PCM: } \theta_w,\theta_q = 0 \ \text{ and } \ \mu_w = \varphi\ ,\ \mu_q = \varsigma. \tag{8}$$

Bårdsen and Nymoen (2009) used this framework to model wage and price formation and US natural rate dynamics. In that study, θ_w and θ_q were estimated to be different from

[3] The two constant terms can defined as the composite terms: $c_w = \tilde{c}_w + \theta_w\, m_w$ and $c_q = \tilde{c}_q + \theta_q m_q$), where $\tilde{c}_w$ and $\tilde{c}_q$ represent autonomous wage and price drift, while the two other terms are implied by the equilibrium correction dynamics.

[4] Alternatively, for wages and consumer prices, p_t, see Bårdsen and Fisher (1999).

zero, and statistically significant. The estimated ι was positive, implying that a long-run relationship between the wage level and productivity, which is in part upheld through equilibrium correction of nominal wage changes. However, the estimated ι was also significantly less than one, implying that there is no equilibrium wage share coming from the process of wage formation.

Bårdsen and Nymoen (2009) used annual times series, and the hourly compensation variable in manufacturing was used as the wage variable. In the present study, we use quarterly time series and the wage variable is compensation in the private business sector, which is a better operationalization of the concept of a macroeconomic wage cost variable. Twelve years of data are also added to the sample used by Bårdsen and Nymoen (2009), which ended in 2004.

2.3 Closing the model

Because focus is on the role of wage-price dynamics, we use a minimal model for the rate of unemployment:

$$\Delta u_t = c_u + \psi_{up}\Delta p_{t-1} - \theta_u u_{t-1} + \varepsilon_{u,t}, \tag{9}$$

with $0 < \theta_u < 1$,$\psi_{up} \leq 0$.

The term Δp_{t-1}, with a positive coefficient, is a simple way of capturing what Stephen Nickell dubbed "latent inflation'", Nickell (1990). His point being that the potential of inflation pressure would not necessarily lead to higher inflation. Instead, increased unemployment was the likely outcome, as more or less forced policy measures were taken to cool down the economy and to steer inflation towards a target (be it implicit or explicit).

A similar policy induced response is relevant during the pandemic-era inflation. However, When we simulate a calibrated version of the WP-EqCM in section 2.4, the parameter ψ_{up} is set to zero, for comparability of the simulations with those of the PCM for U.S. inflation presented by Blanchard and Bernanke (2023).

In order to close the theoretical model, to form a "baseline version", we specify two simple times series models for pi_t and for z_t:

$$\begin{aligned} \Delta pi_t &= g_{pi} + \varepsilon_{pit},\ g_{pi} > 0 \text{ and }, && (10) \\ \Delta z_t &= g_z + \varepsilon_{at},\ g_a > 0. && (11) \end{aligned}$$

As noted, we define the import price as denoted in domestic currency. Hence, implicitly pi_t is the sum of the log of a price index denoted in foreign currency and the log of the nominal exchange rate index.

The model equations given above constitute a dynamic multiple-equation model of the cointegrated type, as formalized in appendix A. The model is a generic model of wage-price dynamics. The PCM-version implies more unit root restrictions on the system than the EqCM-version. Such restrictions are (at least in principle) open to empirical investigation and testing.

2.4 Expectations and the Blanchard and Bernanke (2023) model

A variable category which it is usual to keep in the picture is expectations about wage and price changes. There are two main models of expectations formation used in macroeconomics, the adaptive expectations hypothesis and the rational expectations hypothesis, cf. Pesaran (1987) and Sheffrin (1996) among others. Recent assessments of inflation expectations favour adaptive expectations in combination with survey based measures, over model consistent rational expectations, see Coibion et al. (2018) and Rudd (2021).

Blanchard and Bernanke (2023) is a good example of how survey-based measures can be combined with adaptive expectations — see (39) in the appendix.

In the theoretical framework used by Blanchard and Bernanke (2023), to model pandemic-era inflation in the U.S., adaptive expectation formation about price level changes and long-term inflation targets play a central role. As shown in the appendix, the price and wage equations of their model can be written as:

$$\begin{aligned} \Delta w_t &= \delta\gamma(\pi^*_{t-1} - \alpha\pi^*_{t-2}) + (1-\delta\gamma+\alpha)\Delta p_{t-1} - (1-\delta\gamma)\alpha\Delta p_{t-2} \\ &\quad + \beta(u_t - \alpha u_{t-1}) + s_{wt}, \;\; 0 \leq \alpha, \delta, \gamma \leq 1, \;\; \beta \leq 0, \qquad (12) \\ \Delta p_t &= \Delta w_t + \Delta s_{pt} \qquad (13) \end{aligned}$$

where we have used the same symbols for consumer price, wage and unemployment as above, s_{pt} is a price level shock, and s_{wt} is a shock to the wage change (i.e., to Δw_t). The variable π^*_t is long-run inflation expectations, it can be expressed as:

$$\pi^*_t = \gamma\pi^*_{t-1} + (1-\gamma)\Delta w_{t-1} + (1-\gamma)\Delta z_{pt-1} \qquad (14)$$

(12)-(14) is an expectation augmented PCM-system. As shown in the appendix, the dynamics of the (Δw_t, Δp_t, π^*_t) vector is dominated by a characteristic root equal to one, irrespective of the values taken by the α, δ, γ parameters. Hence, conditional on x_t the system is not dynamically stable. It shares this property with a model that has a vertical long-run Phillips curve, and it is consistent with the natural rate hypothesis.

There is no productivity variable in any of the three equations. However, this is a simplification. In the estimated model, exogenous productivity trends are included in the price and wage equations. Another difference from our model, is that the price equation (13) is written with p_t while we use the aggregate producer price q_t in the corresponding equation (2) above. However, since q and p are connected by the definition (5), the interpretation is the same, namely that prices depend on unit labour costs. A more noteworthy difference is that implicit in (13) is a parameter restriction that corresponds to setting $\theta_q = 0$ in (2). Hence, the price equation (13) can be seen as a special case of our model, and $\theta_q = 0$ is a testable hypothesis.

The wage equation (12) is of the wage-PCM type, and a restriction similar to $\theta_w = 0$ is implicit. However, the appearance of the variable π^*_t, which is defined as long-term inflation expectations, makes (12) stand out. The centrality of expectations is also reflected in the interpretation of the coefficients α, δ and γ in equation (12).

The parameter α is dubbed the the catch-up coefficient by Blanchard and Bernanke (2023), with reference to how workers may seek to make up for past losses of purchasing power. If α is a small positive number, 0.20 for example, catch-up is said to be limited. If it is larger, say 0.6, catch-up is stronger, according to Blanchard and Bernanke. δ and γ are expectations parameters, and we note that it is the product $\delta\gamma$ that matters for wage dynamics. A high value of the product, both δ and γ close to one for example, is called well-anchored inflation expectations. A value closer to zero is referred to as less well-anchored inflation expectations.

Figure 1 shows the model's inflation responses to a one-time shock to the price equation. Specifically, the assumed shock is that the price shock variable s_{pt} rises permanently by one unit in period 0. This implies a one-period shock to price inflation, Δp_t. The graph marked "BB: weak-feedback" shows that the sharp increase in inflation is almost completely reversed after a few periods. The low persistence of inflation in this case reflects that limited catch-up is assumed and the expectations parameters have been chosen in such a way that there is little relationship between the sharp initial rise in inflation and long-run expectations, concretely: $\alpha = 0.2, \delta = 0.9, \gamma = 0.95$.

Note that inflation ends up slightly higher, by 0.06 percent in this simulation. This is a consequence of the unit-shock property mentioned above (the temporary shock is then transformed to a non-zero long-run response). However, this is conditional on an exogenous path for the variable that represent labour market tightness. Presumably, if there is a wish to force the response to zero, that can realistically be achieved by cooling down the economy (maybe not by very much).

The graph labelled "BB: strong-feedback" is from a simulation with a higher catch-up coefficient and expectations parameters that imply weak anchoring, concretely: $\alpha = 0.6, \delta = 0.7, \gamma = 0.9$. The persistence is considerably larger and disinflation will be more costly.

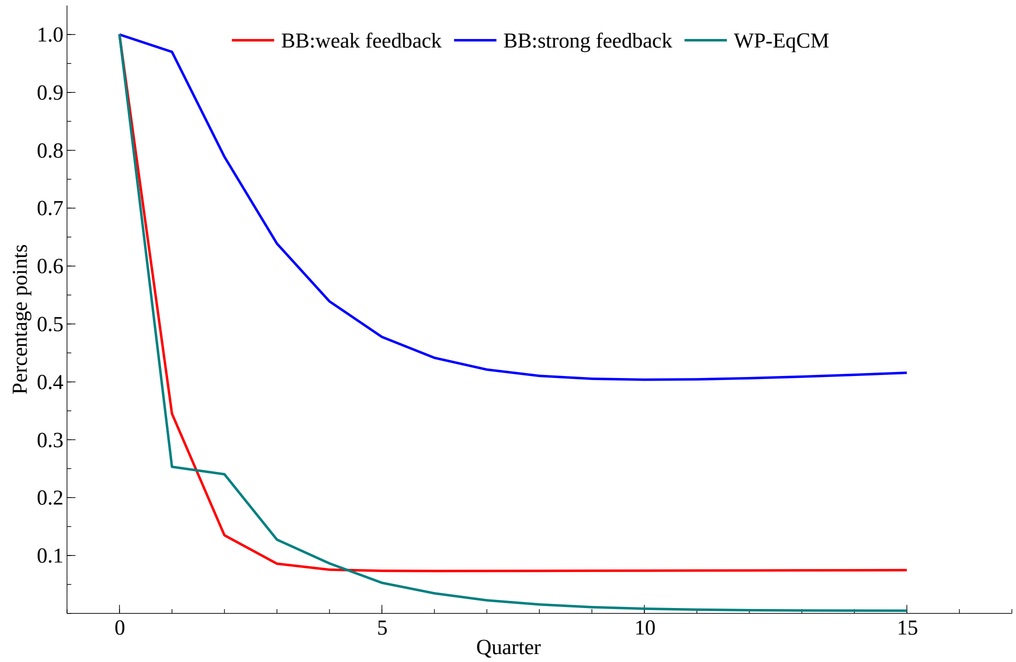

Figure 1: Inflation responses to a 1-period shock to Δp_t, for two alternative calibrations of the stylized model of Blanchard and Bernanke (2023), together with a simulation of a calibration of the stylized WP-EqCM model above. See appendix A and appendix B.

The third graph is obtained by simulation of the WP-EqCM with parameters at reasonable values both theoretically and empirically—see Appendix A. The initial inflation response in this model is also calibrated to unity. In this example, two thirds of the response comes from an impulse to pi_t, the rest is due to a domestic producer price shock.

Our framework has a Phillips curve model with natural rate dynamics as a special case, and it it is possible to also simulate calibrations of it that comes closer to the "BB: strong-feedback" graph in the figure. To force a substantive long-run effect would entail setting the equilibrium correction parameters θ_q and θ_w to zero, as well as specific dynamic price homogeneity restrictions, see Kolsrud and Nymoen (2014). Hence, the theoretical simulations invite empirical modelling and dynamic analysis of the model.

However, while Figure 1 illustrates that the inflation responses may be quite similar in the two models, the same cannot be said for the real-wage responses shown in Figure 2. The figure shows two responses for the WP-EqCM, for the consumer real wage $w - p$ and for the producer real wage $w - q$. The impact response is negative for both, but dynamic responses are different. The magnitude of the producer real wage responses are reduced more or less monotonously, while the consumer real wage responses increase in magnitude for the first four quarters.

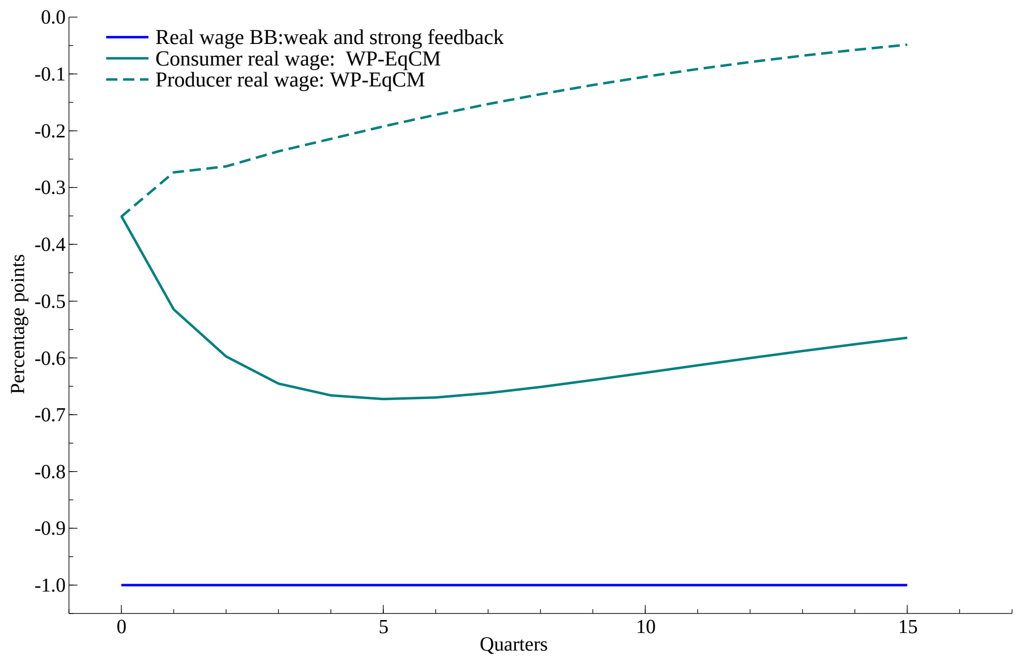

Figure 2: Real wage responses to a 1-period shock to Δp_t for two alternative calibrations of the stylized model of Blanchard and Bernanke (2023), together with a simulation of a calibration of the stylized WP-EqCM model. See appendix A and appendix B.

The real wage responses of the Bernanke-Blanchard model are very different in comparison. They are constant and identical to the price shock. The strength of the feed-back does not play any role for the how the real wage $(w-p)$ responds to the shock. The property is a consequence of (13), since by definition the real wage evolves as:

$$(w-p)_t = (w-p)_{t-1} + \Delta w_t - \Delta p_t$$

and from (13) $\Delta w_t - \Delta p_t = -\Delta s_{pt}$ which is -1 in the period of the shock and 0 is all other periods.

As the two variables π^*_{t-1} and π^*_{t-2} do not appear in our wage-equation (1), one implication is that our equation (1) omits explanatory variables. However, by repeated insertion backwards (14) can be written as an (arbitrary long) moving average of lagged wage change rates. Hence, an implication from Blanchard and Bernanke's model is that equation (1) misses terms like Δw_{t-1}, Δw_{t-2}, and so on. However, that critique is not strong since in our practical modelling we use general-to-specific methodology. It means that lags in differences can be included in the empirical version of the model if found significant. As already noted, our theoretical framework is easily generalized to higher order dynamics (see also the appendix).

If we abstract from the specific theory of Bernanke and Blanchard, and interpret π^*_t more broadly, for example as a function of the inflation target associated with monetary policy (π^{**}). Well-anchored expectations would then entail that $\pi^*_{t-1} = \pi^*_{t-2} = \pi^{**}$, which becomes a constant term. However, a change in the inflation target or disruption of the relationship between π^{**} and π_t^* will induce a break in the constant term. One way of understanding the monetary policies implemented in the U.S., and elsewhere in the Western world in 2022, was that it was driven by a concern that the inflation surge that began in 2021 could lead to that kind of decoupling of inflation expectations from targets. However, as more data from the pandemic and the post-pandemic era becomes available, the constancy (or not) of the intercept, as well as other model coefficients that may depend on expectation parameters can be investigated empirically, which we do.[5]

Turning the argument around, our theoretical framework implies that the stylized model of Blanchard and Bernanke omits import price growth. Although they make many modifications of the model when it is implemented, that trait seems to carry through to the empirical model.

e) Rational expectations and New Keynesian PCMs

Model equations specified with mathematical (rational) expectation about lead variables, for example $E_t(\Delta p_{t+1})$, is the hallmark of the New Keynesian Phillips curve model (NPCM), Galí and Gertler (1999).

At first sight, wage and price equations with explicit lead variables cannot be reconciled with the wage-price model outlined in Section 2. However, following Nymoen (2021), the rational expectation solutions of the price-NPCM, and the wage-NPCM, can be written on equation form as:

$$\Delta q_t = b_{q0} + b_{q1}\Delta q_{t-1} + b_{q2} ws_t + b_{q3} ws_{t-1} + e_{q,t}, \tag{15}$$

$$\Delta w_t = b_{w0} + b_{w1}\Delta\bar{\pi}_{t-1} + b_{w3} u_t + b_{w4} u_{t-1} + e_{w,t}, \tag{16}$$

where ws_t denotes the wage-share: $ws = w_t - q_t - z_t$ and $\bar{\pi}_t$ denotes a "wage-indexation term", which ws specified as $\bar{\pi}_t = 0.25\Delta_4 p_t$ by Galí (2011) in his empirical assessment of the New Keynesian wage Phillips curve.[6] The two error terms are uncorrelated with ws_t and u_t respectively (i.e., under the maintained assumptions of the theory), hence the two equations can be treated econometrically using OLS estimation.

As noted by Rudd (2021), the original long-run NPCM was downward sloping, and this carries over to (16) in particular. Hence, just as for the old PCMs, the equation needs to be restricted with lag coefficients that sum to one ($b_{w1} = 1$ in this simple case) in order to imply no trade off between wage growth and the unemployment rate.

The symbols used to denote the coefficients in (15) and (16) are different from the symbols used in the "corresponding" price and wage adjustment equations in the paragraphs above. This is intentional, as (15) and (16) are based on the underlying microfounded theory. Nevertheless, as "mere" model equations for nominal price and wage changes, (15) and (16) have a lot in common with the WP-EqCM and the PCM. Hence, one can imagine an empirical GUM (General Unrestricted Model) that encompasses model equations within all the three model classes.

[5] As (12) shows, sudden changes in the expectation parameters δ and γ imply structural breaks in the coefficients of the inflation variables.

[6] cf. Galí (2011, Table 1).

3 An empirical econometric model

In this section we discuss the empirical implementation of the model set out above (and in more detail in the appendix).

3.1 The time series variables

The operational definitions of the variables appearing in the theory model are:

Q:	Price index, gross value added, Nonfarm business. 2005=1.
P:	Price index, personal consumption expenditures. 2005=1.
PI :	Price deflator of imports of goods. 2005=1.
W:	Hourly compensation for all employed workers. Nonfarm business. 2005=1
U:	Unemployment rate. Percent.
Z:	Labour Productivity (output per hour) for all employed persons. Non-farm business. 2005=1

The data are quarterly and the variables are seasonally adjusted.

As already noted, the interpretation of the stylized model is not altered if we allow for longer lags and use data based dynamic specification of the equations. This flexibility is valuable since our purpose is an explanatory model of U.S. wage and price dynamics on quarterly data. In addition we include a few more explanatory variables to account more explicitly for the forces affecting inflation:

$CAPU$:	Capacity utilization, total index. Percent of capacity
PO:	Spot crude oil price: West Texas Intermediate (WTI). Dollars per Barrel.
TRA:	Federal transfers. Billion dollars
WAC:	Index of Global Real Economic Activity. Not seasonally adjusted.

Finally, to test the role of (measured) inflation expectations in wage formation in particular, we use the one-year inflation expectations series constructed by the Cleveland Fed. It is called Infexp below.

The time series have been downloaded from FRED Economic Data.[7]

For some of the variables, there is more than one operational definition of the theoretical variable to choose from. For example, the consumer price variable, P, can be operationalized by one of the consumer price indices available, or by the deflator of personal consumption expenditure (U.S. Bureau of Economic Analysis). We use the latter since data for the producer price, Q, and price of imports, PI , is available from the same source.

The source of the wage and productivity series is the Labor Productivity and Costs (LPC) program of the Bureau of Labor Statistics (BLS) which reports labour productivity and compensation data for the non-farm business sector quarterly. Compensation includes "wages and salaries" and "supplements". Champagne et al. (2016) for an analysis of the series' properties compared to the the other main source of hourly wage, from the Current Employment Statistics. In our case, where we model inflation jointly with the variables in the functional income distribution, an argument for using LPC wage data is that it secures internal consistency as the productivity variable in the model is from the same source.

[7] https://fred.stlouisfed.org/

We have included the variable TRA (Federal transfers) in the data set because the literature has brought to attention the potential that the fiscal stimulus over the December 2019 to June 2022 period had become an inflation factor, di Giovani et al. (2023) and Hagedorn (2023) as noted above.

Figure 3 shows plots of the one quarter changes (first row), and four quarter changes (second row) in the logs of W_t, Q_t and P_t.

The correlations between the nominal changes are easiest to spot in the second row where the annual changes are plotted. In the first row, the considerable short-run variation is noticeable, in particular for wage changes. The variability of the wage change rates wage change also appear to have increasing over time, leading to heteroscedasticity as a characteristic in the time series for wages. One explanation of may be that compensation per hour is affected by the changing composition of the employed, between sectors and professions. Another BLS series, the employment cost index, corrects for composition effects, and in future work we intend to use also this measure, although the point just mentioned about consistency with how productivity is measured may still lead us prefer average compensation in the multiple equation model.

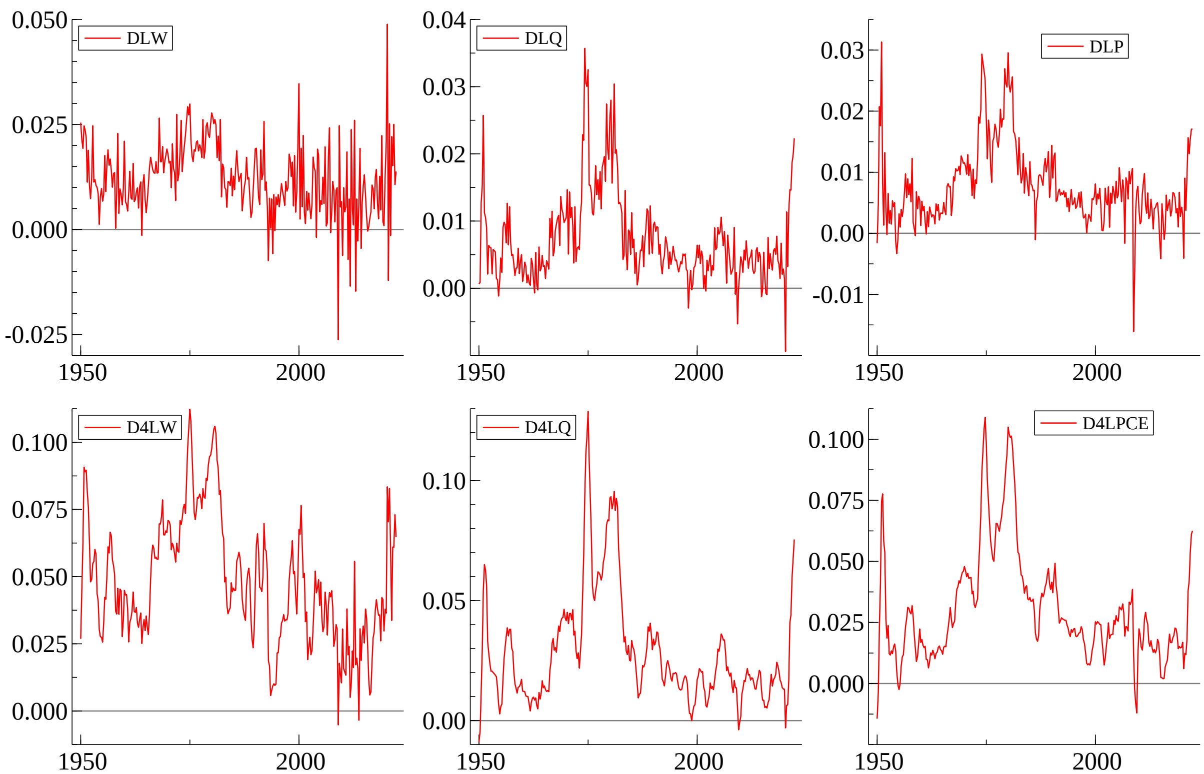

Figure 3: Wage and price change data. Units are relative change from the previous quarter (first row) and from the same quarter in the previous year (annual growth rate).

3.2 Empirical model specification

In the following we present model equations that retain the theoretical framework, in PCM or in EqCM form. However, as the framework is incomplete, it was not enforced without testing. Instead we employ structured variable selection, which starts from general a model with many more variables than in the theory model. This practical specification method at least leaves the researcher with fighting chance of arriving at a final model which is a reasonable approximation to the unknown data generation process (DGP), see Hendry and Johansen (2015) for a concise but accessible exposition.

In brief, our approach has been to embed theoretical model equations in a statistical model with flexible dynamics (additional lags) and allowing for exogenous explanatory variables in the literature on U.S. wage and price inflation. We also make use of indicator saturation estimation, cf. Johansen and Nielsen (2009), as implemented in *Autometrics* in the econometrics software package PcGive, see Doornik and Hendry (2022a,b), following the approach of Hendry and Johansen (2015) by using a tight significance level when testing for breaks, keeping the explanatory variables fixed, and then testing the variables using a looser significance level. The coefficients of the retained indicator variables represent estimated departures from the modelled relationships which apply to the counterfactual situation where there are no breaks in deterministic terms. The final product of our modelling, we hope to show, is a parsimonious multiple-equation model, interpretable as an empirical implementation of the theoretical framework as well as a relevant explanatory model of U.S. wage and price inflation.

In the following, we let lower case letters denote logs of variables. Hence for the wage W_t, the logarithm is $w_t = ln(W_t)$. The relative change is $\Delta w_t \equiv w_t - w_{t-1}$, the annual rate $\Delta_4 w_t \equiv w_t - w_{t-4}$.

The wage equation

As noted above, empirical US-wage equations have typically been specified as Phillips curves, the W-PCM defined above. Based on the theoretical framework and the broader literature on rent-sharing, an alternative to the incumbent W-PCM equation is the W-EqCM where indicators of the functional income distribution play separate roles as explanatory variables of wage growth.

OLS estimates of the empirical wage equation is reported in equation (17) below. It is the model specification reached after starting from a general autoregressive distributed lag model with four lags, and by using the machine learning algorithm *Autometrics* with indicator saturation,cf. Castle et al. (2012), Hendry and Doornik (2014, Ch 19-20). [8] The model equation shows close correspondence with (1) in the stylized model. Changes in producer price (Δq_t), productivity (Δz_t) and consumption price index (Δp_t) index are explanatory variables, at different lags. The standard assumption that wage growth depends on labour market tightness is supported by the inclusion of the unemployment rate, in a

[8] Batch files with code that documents the specification is available, for this model equation and the others in the full model.

non-linear form $(1/U)$ and at lag three.

$$\begin{aligned}\Delta w_t = & - \underset{(0.052)}{0.2} \Delta w_{t-1} + \underset{(0.058)}{0.28} \Delta z_t + \underset{(0.092)}{0.31} \Delta q_{t-1} + \underset{(0.1)}{0.58} \Delta p_t \\ & + \underset{(0.0087)}{0.032} 1/U_{t-3} - \underset{(0.016)}{0.084} [w - q - 0.82z]_{t-1} \\ & + \underset{(0.0063)}{0.029} II_{2000(1)t} + \underset{(0.0045)}{0.022} DI_{2008(4)t} + \underset{(0.0045)}{0.017} DI_{2012(4)t} \\ & + \underset{(0.0067)}{0.048} II_{2020(2)} - \underset{(0.0018)}{0.0018} \end{aligned} \tag{17}$$

OLS 1967(1) – 2023(2)	$\hat{\sigma}100 = 0.62$
AR 1-5 test:	$F(5, 210) = 1.88[0.10]$
ARCH 1-4 test:	$F(4, 218) = 2.51[0.04]$
Normality test:	$\text{Chi}^2(2) = 6.7[0.04]$
Hetero test:	$F(16, 207) = 2.34[0.003]$

What makes (17) different from a wage Phillips-curve, this is the variable $(w - q - 0.82z)_{t-1}$. This is an EqCM-term, the estimated coefficient corresponds to the adjustment parameter $\hat{\theta}_w$ in the theoretical equation (1). Conditional on cointegration, $\hat{\theta}_w$ is highly significant, with t-value -5.2.

We found that the significance of the wage EqCM-term depended on *not* forcing the coefficient of z to be one, which would imply that it is the log of the wage-share (as in the theory model). This result is the same as we discovered in our earlier analysis of an annual data data set, 1967-2004, Bårdsen and Nymoen (2009). The interpretation is that, all things equal a one percent increase in price and productivity go together with a smaller percentage increase in the wage level. Hence, wage nominal wage adjustments alone will not imply that the functional income distribution is stable and without downward secular trend.

Below the estimated equation the sample period is reported in the first row, together with $\hat{\sigma}100 = 0.59$ which is the residual standard deviation in percent. The four last lines below the equation are standard tests of residual mis-specification: For autoregressive residual autocorrelation of order five; ARCH residual heteroscedasticity of order four; Departure from normal distributed error terms; and residual heteroscedasticity due to squares of regressors.[9] p-values for the tests are reported in square brackets.

The most significant test is the "Hetero test". It means that increased variability in the wage change data that we noted above is not well explained by the model equation (despite the inclusion of the dummies noted below). This gives a reason for using heteroscedastic standard errors to check that the robustness of the significance of the individual variables. We found that when heteroscedasticity consistent standard errors (HCSE) were used, the t-value of $\hat{\theta}_w$ changed only marginally, to -5.9. Statistical significance was also robust for the other economic explanatory variables in the wage equation.

There are few retained indicator variables in (17), despite the long sample period (1967(1)-2023(2): There are two impulse indicators, for 2000(1) and 2020(2) in the equation, and there are two differenced indicators, for 2008(4) and 2012(4).

[9]The mis-specification and the other estimation results were obtained by PcGive 16, Doornik and Hendry (2022a).

$DI_{2008(4)t}$ is $+1$ in 2008(4) and -1 in 2009)1) can be associated with the financial crisis. All of the other indicators are also from the 2000's, when the variability of Δw_t is higher than earlier in the sample period.

Of special interest to us is that there is a single indicator variable from the pandemic era, $II_{2020(2)}$ which is 1 in the second quarter of 2020, the first "COVID-quarter". The job losses that occurred in late March and early April 2020 were unprecedented. As a consequence, unemployment rose sharply from 3.8 percent in 2020q1 to 13 percent in 2020q2. However, certain industries were hit harder than others, with the result that labour quality increased substantially. As shown by Stewart (2022), this composition effect can account for the main part of the sharp increases in average wage (compensation) and in labour productivity (see below) in the data for 2020.

The indicator variables in equation (17) are interpretable as location shifts. $DI_{2008(4)t}$ and $DI_{2012(4)t}$ give only short lived temporal shifts, while $II_{2000(1)t}$ and $II_{2020(2)t}$ imply a higher secular trend of the wage level (all other factors kept constant). Another type of structural break has to do with non-constancy regression coefficients. With reference to the Great moderation and the Great recession, Blanchard (2016) and others suggested that the Phillips curve had become flatter, maybe returning to the slope that reigned during the 1960s. That (emerging) consensus about a "flatter Phillips curve" became correlated with important monetary policy deliberations. At the Jackson Hole economic policy symposium in 2020, Federal Reserve Chair Jerome Powell spoke about a new medium-term monetary policy strategy, going for maximum employment as opposed to offsetting deviations from assessments of the natural rate, Powell (2020). However, after the pandemic the question has become whether the Phillips curve has become steeper, see Ari et al. (2023), Crump et al. (2024).

In practice, when we model real world data which is affected by changes both in the economy and in the measurement system, perfect constancy is rarely found. The practical question is instead whether the coefficients are constant enough to assess the explanatory power of the included variables.

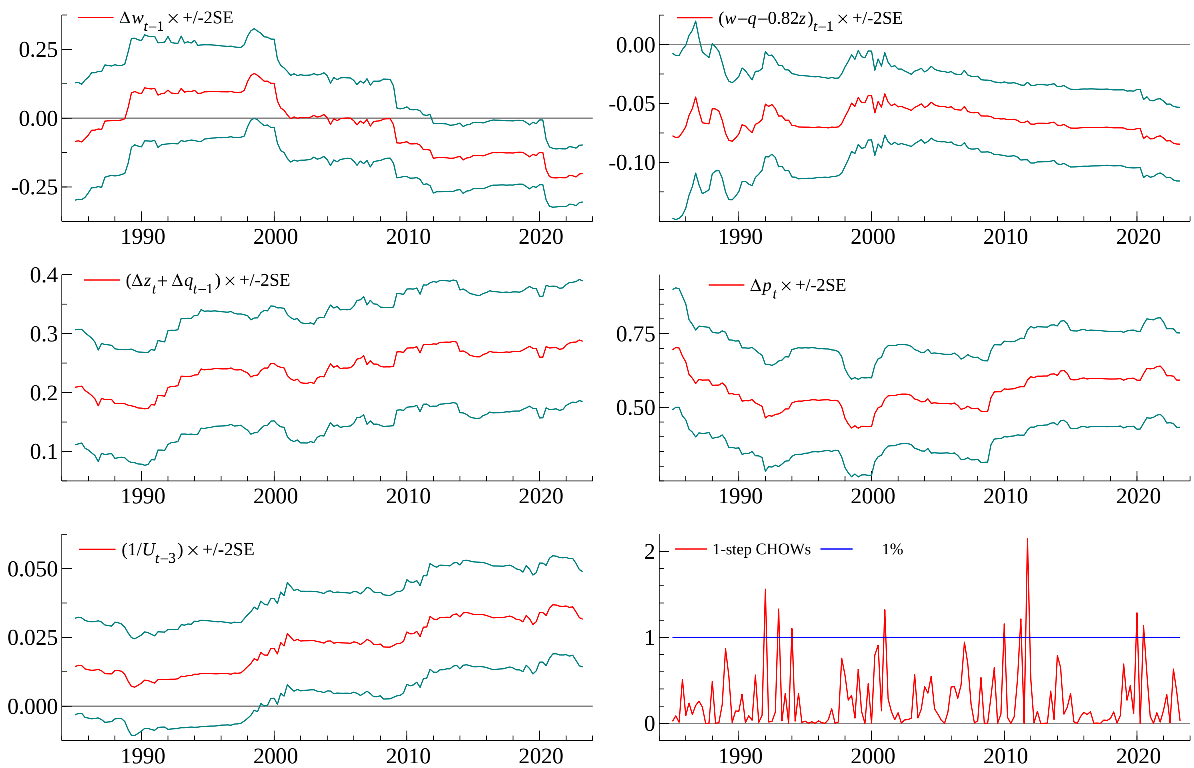

Figure 4: Recursive estimation results illustrating empirical coefficient constancy for the wage equation over the Great moderation, the Great recession and the Pandemic-era.

Figure 4 illustrates relative coefficient inconstancy for the coefficients of equation (17). The first five plots are the coefficient estimates at each point in the shown sample period, together with their approximate 95% confidence intervals (±2SE on either side). In the sixth panel joint parameter constancy is illustrated by plotting the sequence of 1-step Chow tests, scaled by the 1 % critical values for rejecting a single null hypothesis of constancy.

The most fragile coefficient appears to be in the first panel, the coefficient of Δw_{t-1}. It is first positive (albeit insignificant), but shifts to zero at the start of the new millennium and then to the negative value it takes in (17), when the full sample is used. In the main we attribute this to the noticeably more jagged time series for Δw_t after 2000, which is consistent with the change from positive to negative autocorrelation coefficient (conditional on the other variables in the model).

With regards to the changing "slope of the Phillips curve" debate, the fifth panel is of interest. When uncertainty is taken into account, the noticeable drift in plotted coefficient is not a significant change, and taken at face value it goes in the opposite direction of the flattening of the Phillips curve during and after the Great Moderation.

Finally, since it is the $(w - q - 0.82z)_{t-1}$ variable that makes the wage equation stand out from the typical wage-PCM, it is of interest that the coefficient of the variable is quite stable over the whole period shown. Finding that wage equilibrium correction dynamics can be estimated with data from the Great moderation and earlier, is also consistent with our

Table 1: Robustness check of wage model equation (17), with respect to inflation expectations ($Infexp$) and omission of the 1960's and 1970's from the sample:

	I OLS	II IVE	III OLS
Δp_t	0.46^{**}	0.38	0.53^{**}
Δw_{t-1}	-0.23^{**}	$-0.22{*}{*}$	-0.25^{**}
Δz_t	0.35^{**}	$0.34{*}{*}$	0.33^{**}
Δq_{t-1}	0.19	0.23	0.07
$1/U_3$	0.05^{**}	0.05^{**}	0.05^{**}
$[w - q - 0.82z]_{t-1}$	-0.11^{**}	-0.10^{**}	-0.09^{**}
$II_{2000(1)}t$	0.03^{**}	0.03^{**}	0.03^{**}
$DI_{2008(4)}t$	0.02^{**}	0.02^{**}	0.02^{**}
$DI_{2012(4)}t$	0.02^{**}	0.02^{**}	0.02^{**}
$II_{2020(2)}t$	0.04^{**}	0.04^{**}	0.04^{**}
$Constant$	-0.004	-0.004	-0.005
$Infexp_t$			-0.002
$Iinfexp_{t-1}$			0.002
Sargan-IV		$\chi^2(1) = 3.0$	

Note: Sample period 1982(2)-2023(2). ** = significant at 1 %.

earlier modelling of annual wage-price data.

In appendix D additional results are reported which demonstrate that the empirical equation is robust when IV-estimation is used, which is consistent when the inclusion of contemporaneous explanatory variables represent a source of simultaneity bias in the OLS estimators.

Finally, in this section on the wage equation, we test the robustness of the interpretation that the dynamic specification is consistent with adaptive inflation expectations. If the hypothesis is not incorrect, a variable that measures inflation expectation should be insignificant when added to wage equation (17).

We use the one-year inflation expectations series constructed by the Cleveland Fed, which was used by Bernanke and Blanchard in their empirical model. The series starts in 1982(1), so the sample is shorter than the sample used for the specification of the model. However, that gives a direct test of robustness with respect to the exclusion of the information in the from the 1960s and 1970s.

The model in column I of table 1 is therefore equation (17) re-estimated on the sample that starts in 1982(2) (to allow one lag of the expectations variable). The results supplement the recursive graphs, and shows that with the exception of Δq_{t-1}, the explanatory variables retain their numerical and statistical significance.

In column II, the expectations variables Infexp_t and Infexp_{t-1} are used as instruments for the contemporaneous price increase variable Δp_t in the model equation. Therefore, the Sargan-IV test for validity of the instruments is reported at the bottom of the column, Sargan (1958,1964). The estimated coefficient of Δp_t, although somewhat reduced, must be said to be robust with respect to the change in estimation method.

Finally, in column III, the expectations variables are included as regressors in the model equation. Individually they are insignificant, and the test of join significance also gets high p-value (0.21, not shown in the table).

As noted, Δq_{t-1} is insignificant on the shortened sample, and the estimated coefficient becomes reduced when the expectations variable is included in the model equation (column III). Hence, Δq_{t-1} may seen as a dubious explanatory variable in model equation (17). It is of interest in further work to investigate more closely if it is a proxy for inflation expectations. For the time being, it seems that the inflation expectations variable does not contribute significantly to our explanatory model of wage growth.

The producer and consumer price equations

The empirical equation for Δq_t in (18) has change in oil-prices (over two quarters, $\Delta_2 po_t$) and in productivity (Δz_t) as contemporaneous explanatory variables. The lagged change in the import price index (Δpi_{t-1}) and the second lag of the dependent variable ($\Delta_2 q_{t-2}$), were also retained as explanatory variables.

$$
\begin{aligned}
\Delta q \;=\;& \underset{(0.019)}{0.22}\,\Delta_2 q_{t-2} - \underset{(0.025)}{0.11}\,\Delta z_t + \underset{(0.008)}{0.036}\,\Delta pi_{t-2} \\
&+ \underset{(0.00086)}{0.0076}\,\Delta_2 po_t + \underset{(0.011)}{0.031}\,\Delta capu_{t-2} \\
&- \underset{(0.01)}{0.1}\,[q_{t-1} - 0.69 w_{t-1} + 0.21(z-pi)_{t-1} \\
&\qquad +0.04(po_{t-1} - (SI_{1972(1)t} + SI_{1986(2)t} + SI_{1999(1)t})] \\
&+ \underset{(0.0028)}{0.012}\,\text{II}_{1998(1)t} + \underset{(0.0017)}{0.018}
\end{aligned}
\tag{18}
$$

OLS $1967(4)-2023(2)$	$\hat{\sigma}100 = 0.28$
AR 1-5 test:	$F(5,210) = 0.62[0.68]$
ARCH 1-4 test:	$F(4,215) = 1.73[0.14]$
Normality test:	$\text{Chi}^2(2) = 4.17[0.12]$
Hetero test:	$F(12,209) = 2.69[0.0022]$

Parallel to the wage equation, there is an EqCM-term in (18), with a significant estimated coefficient $\hat{\theta}_q = -0.1$. The EqCM-variable contains the lagged wage level, the import price index, oil price and the productivity variable. The interpretation is that in a hypothetical steady state, the estimated long-run elasticity of the price Q level with respect to W is +0.7, +0.2 with respect to PI, and +0.04 with respect to the oil-price. The estimated long-run elasticity with respect to a permanent productivity change is −0.2.

According to the hypothesis of normal cost pricing, the long-run elasticities of W and Z is equal with opposite signs. However, that hypothesis was not supported by the data when (18) was estimated. If it is enforced, the estimated $\hat{\theta}_q$ becomes −0.006, hence zero in practice.

The indicator variables in (18) are for periods and single quarters from the three last decades of the previous century. There are no dummies from the pandemic-era in this equation. Three of the indicators are step-dummies that are restricted to be part of the EqCM-variable, implying that the mean of the hypothetical steady-state relationship for q was shifted in 1972, 1986 and in 1999.

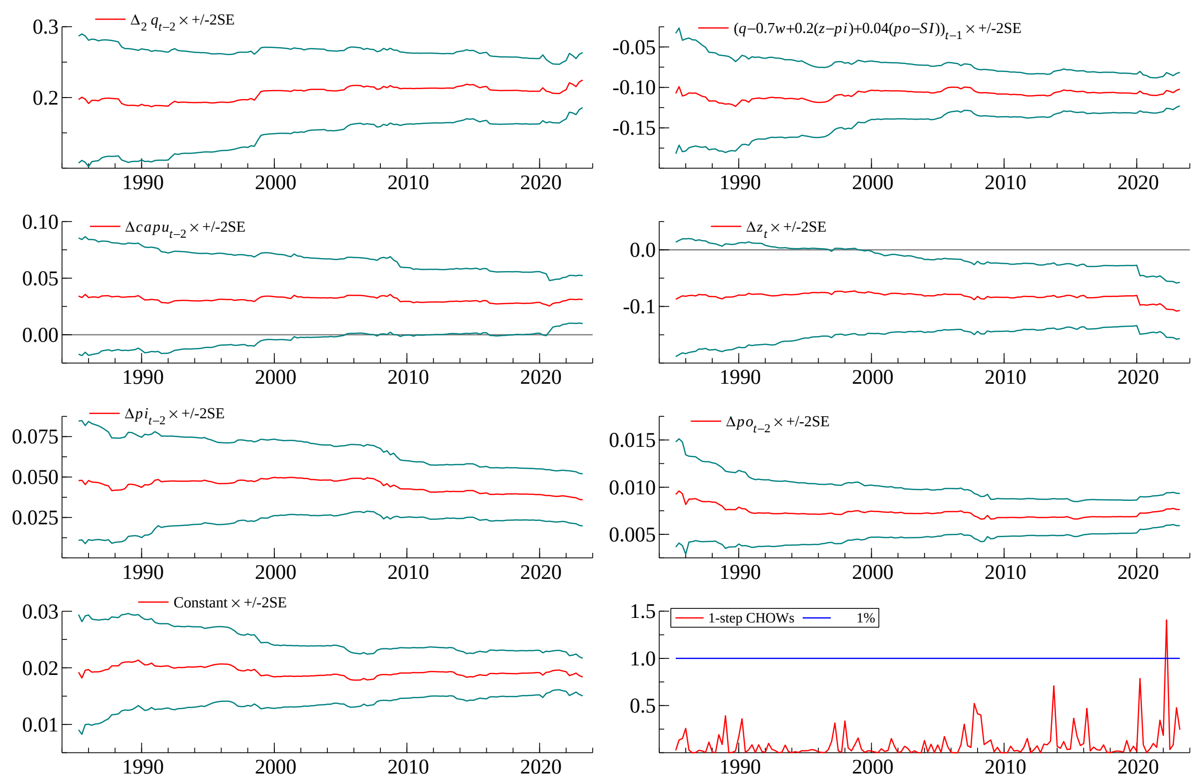

Figure 5: Recursive estimation results illustrating empirical coefficient constancy for the producer price equation over the Great moderation, the Great recession and the pandemic-era.

Figure 5 shows the constancy of all the regression coefficients and the constant term. The high degree of parameter constancy over this 40-year period is striking. The pandemic-era may still be an exception, since there is a significant Chow-test in 2022(2). It reflects a one-step forecast error, and can maybe be interpreted as a price-shock, although it was not retained by the automatic algorithm for detection of breaks. IV estimation results for the equation is shown in Appendix D. Coefficient estimates do not depend in any important way on the estimation method.

Turning to the model equation for the consumer price index, equation (19) includes the expected explanatory variables, Δq and Δpi. Also note the direct effect of growth in transfers (Δtra_t), albeit with opposite signs, supporting that the huge transfers can give a separate impulse to inflation.

The equilibrium adjustment variable has coefficient $\hat{\theta}_p = -0.04$ which is numerically smaller than in the two first equations, but still statistically significant conditional on cointegration. As the producer and import price variables (q and pi) are in the adjustment term, the interpretation is that the secular trend in the consumer price index is correlated with both of them, but the weight on producer prices is much larger than on import prices.

A particular feature of the model is that the transfer variable also modifies the estimated long-run relationship. This effect must to a large extent be attributed to the COVID period. As shown above, transfers to the public rose sharply up to level hitherto unseen, before falling back. That said, the implication of our estimated equation is that huge transfers may drive a temporary wedge between the estimated trend in consumer prices and the "determinants" of the trend: domestic producer prices and prices of imports.

$$\begin{aligned}\Delta p_t \;=\; & \underset{(0.028)}{0.47}\ \Delta q_t \ +\ \underset{(0.014)}{0.089}\ \Delta_2 q_{t-2} \ +\ \underset{(0.0044)}{0.099}\ \Delta pi_t \ +\ \underset{(0.0012)}{0.0031}\ \Delta_3 \Delta tra_t \\ & -\ \underset{(0.0046)}{0.04}\ [p_{t-1} - 0.96 q_{t-1} - 0.04 pi_{t-1} - 0.04 tra_{t-1}] \\ & +\ \underset{(0.0011)}{0.0057}\ (II_{1973(3)t} - II_{1974(2)t}) \\ & -\ \underset{(0.0015)}{0.0079}\ II_{1975(1)t} \ -\ \underset{(0.001)}{0.0046}\ DI_{1975(2)t} \ -\ \underset{(0.0013)}{0.0092} \end{aligned} \tag{19}$$

OLS 1968(1) − 2023(2)	$\hat{\sigma}100 = 0.15$
AR 1-5 test:	$F(5,208) = 1.71[0.13]$
ARCH 1-4 test:	$F(4,214) = 1.86[0.12]$
Normality test:	$\text{Chi}^2(2) = 10.75[0.0046]$
Hetero test:	$F(22,199) = 2.26[0.0016]$

The results so far can be summarized as giving empirical evidence of joint dependency between wage and price setting, and that the interaction takes two forms: between the respective growth rates and through the adjustment of growth rates to the lagged wage and price levels. Significant explanatory factors are the oil price, the price of imports, labour market tightness and how productivity evolves. In addition come the effects of transfers on consumer prices, which may have been numerically significant during the COVID-era.

Productivity equation

The productivity equation (20) is a generalization of the simple autoregressive process (11) in the theory framework. In the empirical version, the productivity growth rate is affected negatively by import price changes (Δpi_t), which may reflect that value added reacts faster than hours worked when there is a price shock. The rate of unemployment also have statistical explanatory power, with the expected positive sign.

$$\Delta z_t = \underset{(0.047)}{0.24} (\Delta w_t - \Delta q_t) - \underset{(0.016)}{0.073} \Delta pi_{t-1} + \underset{(0.0018)}{0.0081} u_t$$
$$- \underset{(0.016)}{0.1} [z_{t-1} - 1.2(w-q)_{t-1} + 0.07pi_{t-1}] - \underset{(0.0032)}{0.01}$$

OLS 1967(4) − 2023(2)	$\hat{\sigma}100 = 0.67$	(20)
AR 1-5 test:	$F(5,213) = 1.1650[0.3275]$	
ARCH 1-4 test:	$F(4,215) = 1.7108[0.1487]$	
Normality test:	$\text{Chi}^2(2) = 4.7536[0.0928]$	
Hetero test:	$F(10,214) = 2.2884[0.0227]$	

The estimation results show that the rate of unemployment has a significant and positive coefficient. It is an important effect to have in the model, as it is one way of representing a consequence of the dramatic job loss during the first year of the pandemic, which was to increase the quality of labour and hence to lift average labour productivity, Stewart (2022).

Another noteworthy explanatory variable is the EqCM-term with estimated coefficient $\hat{\theta}_z = -0.1$. As the coefficient is statistically significant, it implies a long-run relationship between productivity, the real-wage $(w-q)$ and the level of the import price index pi. The long-run elasticity of $(w-q)$ is 1.2, much smaller for pi. The non-homogeneity that pi represents may be difficult to rationalize in economic terms, but it helps the identification of the long-run wage equation in particular, since the EqCM term in (1) excludes the import price index.

We now get to the more marginal equations of the model, for import price (pi), rate of unemployment (U), and capacity utilization ($CAPU$).

Import price equation

In a detailed empirical analysis of the drivers of U.S. import price inflation in the period from 2018(1)-2023(1), Amiti et al. (2024) found that global shocks dominated for most of the pandemic period. After the middle of 2022, when global import price inflation subsided, they found that idiosyncratic U.S. demand and supply components gained in importance.

In model equation (21), the price of energy, represented by the oil-price po_t, fits into that picture, since the price of oil and other energy forms increased sharply when the economies opened up and Russia invaded Ukraine. It was a global shock.

$$\Delta pi_t = \underset{(0.043)}{0.45} \Delta pi_{t-1} + \underset{(0.006)}{0.092} \Delta po_t - \underset{(0.0063)}{0.022} \Delta po_{t-2}$$
$$- \underset{(0.012)}{0.074} II_{2008(4)t} - \underset{(0.015)}{0.036} (pi - 0.18po)_{t-1} - \underset{(0.0096)}{0.023}$$

OLS 1981(1) − 2023(2)	$\hat{\sigma}100 = 1.1$	(21)
AR 1-5 test:	$F(5,159) = 2.53[0.03]$	
ARCH 1-4 test:	$F(4,162) = 1.38[0.24]$	
Normality test:	$\text{Chi}^2(2) = 0.60[0.74]$	
Hetero test:	$F(8,160) = 2.14[0.08]$	

Unemployment rate and capacity utilization equations

In the model, the rate of unemployment plays a role in the inflation process through wage-setting, and in a highly non-linear way. We do not aim at developing anything but a modified autoregressive model for the rate of unemployment, that can be included in the model for the purpose of dynamic (multi-step) forecasting. The same can be said about the endogenization of capacity utilization, which is needed, since it is a variable in the product price equation.

$$
\begin{aligned}
U_t = \; & \underset{(0.025)}{1.5}\, U_{t-1} - \underset{(0.026)}{0.47}\, U_{t-2} - \underset{(0.014)}{0.06}\, U_{t-4} \\
& + \underset{(1.5)}{3.5}\, \Delta(w-q)_{t-4} - \underset{(0.00038)}{0.0014}\, \Delta_2\, WAC_{t-1} \\
& + \underset{(0.12)}{0.94}\, \left(II_{1975(1)t} - II_{1975(3)t} + II_{1980(2)t}\right) \\
& - \underset{(0.096)}{0.47}\, (SI_{1981(3)t} - SI_{1982(4)t}) + \underset{(0.19)}{8.8}\, DI_{2020(2)t} \\
& + \underset{(0.057)}{0.28}
\end{aligned}
\tag{22}
$$

OLS 1969(1) – 2023(2)	$\hat{\sigma} = 0.207$
AR 1-5 test:	$F(5, 203) = 0.50530[0.77]$
ARCH 1-4 test:	$F(4, 210) = 1.0470[0.38]$
Normality test:	$\text{Chi}^2(2) = 1.4442[0.49]$
Hetero test:	$F(32, 185) = 2.1827[0.007]$

$$
\begin{aligned}
CAPU_t = \; & \underset{(0.041)}{1.4}\, CAPU_{t-1} - \underset{(0.062)}{0.35}\, CAPU_{t-2} - \underset{(0.039)}{0.14}\, CAPU_{t-3} \\
& + \underset{(4)}{18}\, \Delta_2 z_t + \underset{(0.0012)}{0.0069}\, \Delta_2\, WAC_t - \underset{(3.9)}{14}\, \Delta_2(w-q)_{t-2} \\
& - \underset{(0.48)}{9.5}\, DI_{2020(2)t} + \underset{(1.1)}{3.6}
\end{aligned}
\tag{23}
$$

OLS 1981(4) – 2023(2)	$\hat{\sigma} = 0.60$
AR 1-5 test:	$F(5, 154) = 1.7300[0.13]$
ARCH 1-4 test:	$F(4, 159) = 3.3265[0.01]$
Normality test:	$\text{Chi}^2(2) = 2.7125[0.25]$
Hetero test:	$F(32, 185) = 2.8809[0.007]$

The complete model: A block-recursive system

Taken as a whole, the above model equations imply a block recursive system: In the first block po_t, WAC_t and tra_t are determined (from given initial conditions). In the second block, w_t, q_t, p_t, z_t, u_t and $CAPU_t$ are jointly determined, conditional on po_t, WAC_t and tra_t.

Within sample, the conditioning can be on historical values of oil price, world activity and transfers (po, WAC_t and tra_t), which exploits the explanatory power of these three exogenous variables. For analyses of responses to shocks and to forecast, we make use of estimated equations for po and WAC_t which are reported in the appendix.

Figure 6 summarizes the dependencies in the model.

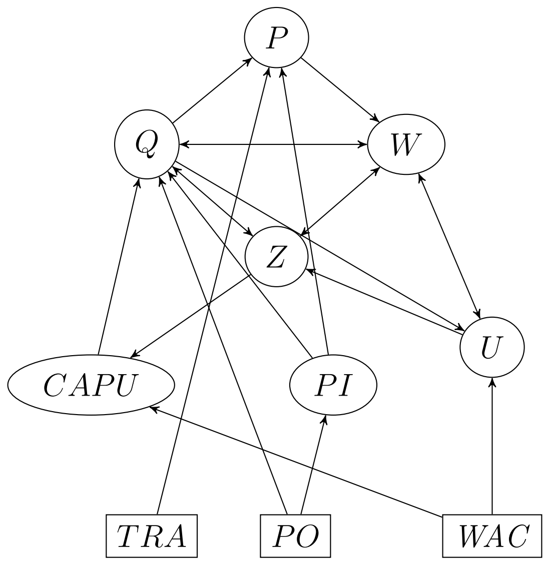

Figure 6: Dependencies between the variables in the empirical wage-price model. W (wage), Q (producer price), P (consumer price), PI (price of imports), U (unemployment rate), $CAPU$ (capacity utilization), Z (labour productivity), PO (oil-price), WAC (world economic activity) , TRA (transfers).

4 Simulating the model

One way to illustrate the corresponding quantitative dependencies is to simulate a scenario where there is a shock to the model equations for the import price index and for the oil price. This is illustrated in Figure 7.

The plots in the figure show the dynamic responses to a joint shock to the error terms in the two equations (namely (21) and (51)). In the scenario, the shock hits in 2020(1). As the two first plots show, the two variables immediately deviate from their baselines by 10 percentage points, and this effect last for the rest of 2020. Subsequently, the effect goes away rather quickly though.

Figure 7: The effects to key variables of the full model of an impulse of 0.1 to import price and oil price equations. All variables except the unemployment rate are annual changes (four quarter relative changes). Deviations of shock-simulation from baseline-simulation. Units on all the vertical axes are percentage points. 95 % uncertainty bounds in dashed lines (bootstrap).

4.1 Before COVID-19: The Great Moderation and the Great Recession

Figure 8 shows dynamic simulation results for the period 1980(1)-2020(1), conditional on the actual values of the exogenous variables po_t, WAC_t and tra_t and the estimated structural breaks (impulses and step) in the empirical model documented immediately above.

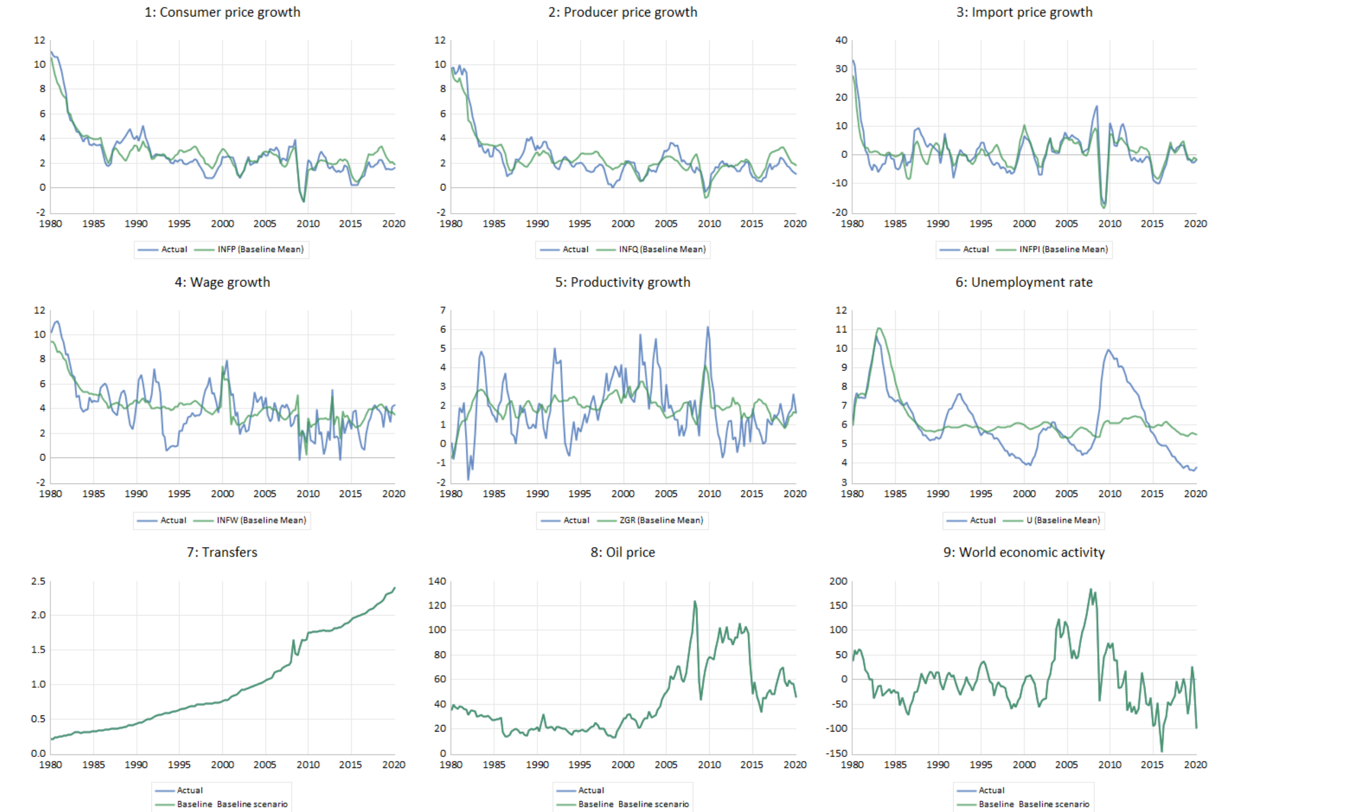

Figure 8: Dynamic model simulation 1980(1)-2020(1), conditional on WAC, po, and tra. Units are percent. The five first panels show four quarter changes. Panel six shows the rate of unemployment. The third row shows the exogenous variables (raw data). Units are billion USD (TRA), USD (PO) and index units (WAC).

The two first panels show how well the model explains the two (price) inflation variables, $\Delta_4 p_t$ and $\Delta_4 q_t$ over the four decades long simulation period. As the estimated equations for Δp_t and Δq_t above document, there is a limited number of indicator variables for breaks in this period. As just noted, in the Δq_t equation (18) there are shifts in the mean of long-run relationship in 1972(1), 1986(1) and in 1999(1). A change in the mean of a long-run relationship can be interpreted as a change in the steady-state growth rate of the affected endogenous variable, not unlike the role played by Δs_{st} in equation (13) in the Bernake-Blanchard model. Hence one interpretation of how well the model simulation fits for price inflation during the Great moderation is that it represents a lowering of price expectations, or others developments that had the same effect, by the step-dummies just mentioned.

In the Δp_t equation (19) there are only short-run fluctuations in 1973-1975 captured by differenced indicators.

Since, in the model, the price inflation is conditional on the relative change in the import price index (but not the other way round) the plot that shows actual and simulated $\Delta_4 pi_t$ in Figure 8 gives additional insight. According to equation (21), the import price index depends on the oil-price, and on a single impulse indicator in 2008(4). It can be noted how fast $\Delta_4 pi_t$ came down in the early, 1980s. Domestic inflation was reduced more gradually as the two first plots show. The next surge in U.S. import inflation happened in the pandemic era, and therefore it is of interest to see whether a similar adjustment pattern can be found for that period (see "COVID-19 and after" below).

The fourth plot shows the simulation results for annual wage growth. Compared to the first three plots, the model does a poorer job in explaining wage inflation. Although the secular reduction in inflation during the Great Moderation is explained, the model fails to account for the persistent low nominal wage growth in 1993-1995. The model tracks wage growth better during the Great recession, albeit aided by two differenced indicator variables, in 1980(4) and 2012(4), cf. (17).

The last plots in the second row show that the explanatory power of the model is a good deal weaker for productivity growth (plot 5) and unemployment (plot 6). However, the simulated productivity growth rate appears to be unbiased, implying that the simulated productivity level does not drift too far from the actual, which would have damaged the simulated values for wage and prices through the EqCM-terms of the model.

Unemployment is not very well explained after 1990, where the solution graph appears to give a near constant rate, despite conditioning on the variation in world economic activity (WAC), which is an exogenous variable in this simulation. Viewed together with the price and wage plots, it is notable that inflation and wage growth are tracked rather well also in periods where the model produces large errors for the unemployment rate. In this way, the model simulation can be said to indicate a weaker association between labour market pressure and inflation than often seems to be taken for granted when policy measures are discussed. One reason for this model property is easy to spot: the non-linear functional form in the wage equation. The conventional view may still be correct though. And it goes without saying that explaining unemployment better would not have done anything but good for how well the model explains inflation.

4.2 COVID-19 and after

The job losses that occurred in late March and early April 2020 were unprecedented. As as result unemployment rose sharply from 3.8 percent in 2020q1 to 13 percent in 2020q2. However, certain industries were hit harder than others, with the result that labour quality increased substantially. As Stewart (2022) convincingly explains, this composition effect can account for the main part of the sharp increases in average wage (compensation) and in labour productivity in the data for 2020(2).

The cause of these dramatic changes was the forced and voluntary steps that were taken to protect public health. Hence, in economic modelling terms it was a huge shock form outside. In our model, it is captured by the indicator variable which is +1 in 2020(2) and zero elsewhere. It appears in two equations of the model: The wage equation (17) and the unemployment equation (22). Interestingly, the algorithm we used did not include it in the productivity equation.

In order to check the model's explanatory power in the pandemic era, we therefore condition the simulation on 2020(2) and solve the model the period 2020(3)-2023(2). Since there are no indicator variables in any of the equations, the only forcing variables are the three exogenous variables: transfers (TRA) , oil-price (PO), and world economic activity (WAC).

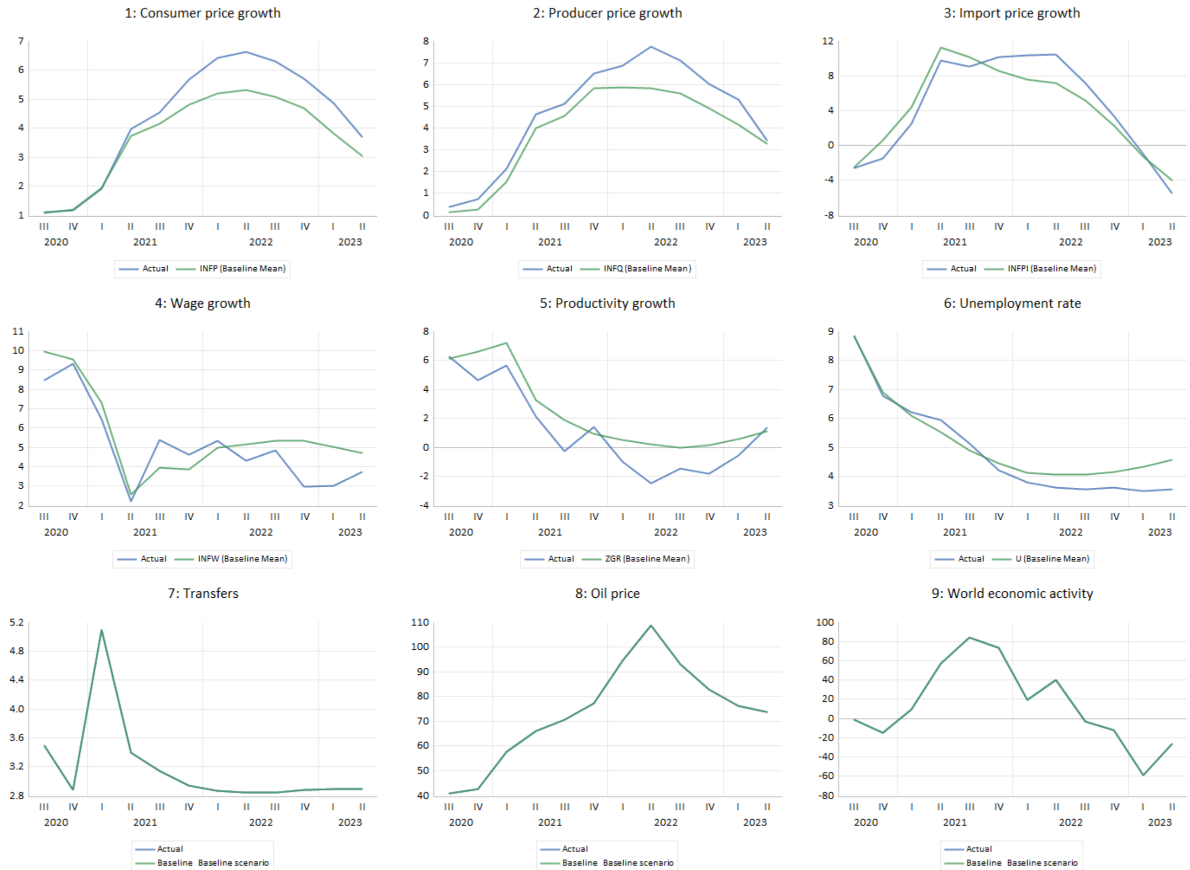

Figure 9: Dynamic model simulation 2020(3)-2023(2), conditional on TRA, PO and WAC. The five first panels show four quarter percentage changes. Panel six shows the rate of unemployment. Units are percent in the first six plots. The third row shows the exogenous variables (raw data). Units are billion USD (TRA), USD (PO) and index units (WAC)

.

The plots in the first row in Figure 9 show that for five quarters, from 2020(3) to 2021(3) the model simulation tracks the increase in both domestic price inflation and in imported inflation. The outside inflationary forces became strong towards the end of 2020. The price of petroleum products started on a steep rise that peaked in 2022(2) after the Russian invasion of Ukraine. However, the price shock was broad, as the increase in import price growth to ten percent shows (third panel in first row).

Attention has been drawn towards the fiscal stimulus over the December 2019 to June-2022 period, di Giovani et al. (2023) and Hagedorn (2023). As shown above, the increase in transfers is an explanatory variable of consumer price inflation in our model. The plotted series for transfers in the third row shows that this shock hit in 2021(1). Because of the dynamics of prices and wages, the effects of the transfers-shock are likely to affect the simulated values for at least the rest of 2021.

The model also explains wage growth well during the first phase of the pandemic (first plot in the second row), and it is interesting to note that wage growth and price inflation moved in opposite directions. Technically, this is made possible in the model because of the important role that initial conditions play for the model solution when they are far removed from long-run equilibrium values, a condition almost certainly met in this case. In terms of economic interpretation, the reduction in wage inflation is also consistent with the large composition effects becoming less dominant for wage growth as we move away from the first quarter of the pandemic.

The model also gives a reasonably good explanation of wage growth in 2022, but for consumer and producer price inflation there is a gap between actual and simulated values. For consumer price growth the largest difference is 2022(2) when actual inflation was 6.6 percent, while the simulated rate became 5.0 percent. The "missing inflation" may be seen as an accumulation of small but systematic errors (estimated constant terms are the usual suspects). However, this does rule out the possibility that the inflation that the model misses can be due to other factors. For example, like other authors have done, it is possible to condition the consumer price equation on the price of food and energy. This will be explored in our further work with this project.

5 Summary

We have specified an empirical model of U.S.inflation which is built around a wage-price spiral core. In the model, producer prices and productivity are related to wage adjustments both in the short and in the long run, where the wage level is related to factors influencing industrial prosperity — the ability to pay in the firms that set wages ("rent-sharing"), giving room for effects from both consumer and producer prices. Although the wage equation is therefore distinct from a wage Phillips curve, it includes other explanatory variables that are well known from studies of US wage Phillips curves. The empirical model explaining producer prices includes an import price index and the price of oil. The model for consumer prices contains additional effects of transfers fuelling inflation.

Dynamic model simulation showed that the model explained quite well the long-term behaviour of wages and prices over the four decades that include the Great Moderation and the Great Recession. The simulated fit of the model for this long period was aided by the relatively few, but still significant, location shifts that are included in the core equations. Those location shifts have the double interpretation as structural breaks, but also as conditioning factors that robustify the estimation of the derivative coefficients in the model equations that determine the dynamic multipliers and impulse responses.

The estimated equation for the producer price index is an example. It contains three step-dummies (for breaks in 1972(1), 1986(2) and 1999(1)) which helps the dynamic simulation of the complete model stay "on track". However, as Figure 5 showed, the coefficients of the economic explanatory variables in the equation are quite constant over the sample. As we see it, this type of constancy increases the relevance of the model for comparative dynamics.

Regarding the pandemic era, our results indicate:

- Wage growth was only moderately high in the period before the pandemic, in part due to labour market tightness.

- When the pandemic hit, the sudden surge in unemployment due in particular to layoffs of large swaths of service sector workers, raised both productivity and compensation rates. As this was a pure composition effect, it was always likely to be temporary.

- The increased inflation which started in 2021 was therefore dependent on other factors than wage costs to evolve as it did:

- A strong and broad increase in international prices, energy prices and transfers were factors that contributed to pandemic era inflation.

In terms of simulated fit, the complete model explained wage growth well during the first phase of the pandemic as well as giving a reasonably good explanation of wage growth in 2022.

Bringing import price inflation into the model seems to reduce the "need for" a large domestic price shock to explain inflation in 2020 and 2021. But not entirely, and in 2022 there was a considerable gap between between actual and simulated inflation. Explaining this gap will be explored in our further work with this project.

The wage equation was tested for omission of the inflation expectation variable that Bernanke and Blanchard focus on, and it was found to be robust. This does not imply that an integrated approach, with endogenous expectations, should not be attempted in further work.

A Cointegrated VAR representation of the theoretical wage-price model

(1), (2), (10), (9) and (11) constitute a system of equations that can be written in matrix form:

$$\boldsymbol{A}_{s0}\Delta\boldsymbol{y}_t = \boldsymbol{\alpha}_s\boldsymbol{\beta}'\boldsymbol{y}_{t-1} + \sum_{i=0}^{p-1}\boldsymbol{A}_{si}\Delta\boldsymbol{y}_{t-1-i} + \boldsymbol{C}_s\boldsymbol{D}_t + \boldsymbol{\varepsilon}_{st}, \tag{24}$$

where the vector $\boldsymbol{y}_t$ has five elements:

y_1 = gdp-deflator,q
y_2 = wage, w
y_3 = unemployment rate, u
y_4 = import price, pi
y_5 = productivity, z.

The consumer price index p is not included as an element in $\boldsymbol{y}_t$ because it has been substituted by the use of the definition (5). However, when a solution for $\boldsymbol{y}_t$ has been found, the associated solution for inflation Δp_t is obtained by using the differenced version of (5), namely $\Delta p_t = \phi\Delta q_t + (1-\phi)\Delta pi$.

The matrix with contemporaneous coefficients is denoted $\boldsymbol{A}_{s0}$. The equations were specified with first order dynamics. But inclusion of longer lags is theoretically unproblematic, and this possibility is represented by the terms $\boldsymbol{A}_{si}\Delta\boldsymbol{y}_{t-i}$ in the SEM (24).

$\boldsymbol{D}_t$ represents deterministic terms and can include the intercept terms in the equations above, but also deterministic trend, seasonal dummies, impulse indicators and step-dummies.

As mentioned in the main text, for some of the estimated equations, step-dummies can be restricted to be in the cointegration space.

For the WP-EqCM, $\boldsymbol{\alpha}_s$ is the (5×3) matrix with equilibrium correction coefficients. Row 4 and 5 consists of zeros while the upper (5×3) partition is diagonal with θ_q, θ_w,θ_u as non-zero elements in the main diagonal. The implied $\boldsymbol{\beta}$-matrix with the coefficients of the long-run relationship is:

$$\boldsymbol{\beta} = \begin{pmatrix} 1 & -(1-\omega(1-\phi)) & 0 \\ -1 & 1 & 0 \\ 0 & \varpi, & 1 \\ 0 & -\omega(1-\phi) & 0 \\ 1 & -\iota & 0 \end{pmatrix} \tag{25}$$

For the PCM, $\theta_q = \theta_q = 0$, while $\theta_u > 0$, hence $\boldsymbol{\beta}'$ is then a (1×5) vector with one in the third row and zeros elsewhere. In this case we can redefine $\boldsymbol{y}_t$ in such a way that the third element is u_t, and replace θ_u with $(\theta_u + 1)$ in $\boldsymbol{\alpha}_s$. Finally, we make use of the conventions for μ_q and μ_w above, so that φ and ς logically become element in the $\boldsymbol{A}_{s1}$ matrix.

Subject to invertibility of $\boldsymbol{A}_{s0}$ the reduced form is:

$$\Delta \boldsymbol{y}_t = \boldsymbol{\alpha}\boldsymbol{\beta}'\boldsymbol{y}_{t-1} + \sum_{i=0}^{p-1} \boldsymbol{\Gamma}_i \Delta \boldsymbol{y}_{t-1-i} + \boldsymbol{C}\boldsymbol{D}_t + \boldsymbol{\varepsilon}_t, \tag{26}$$

where the matrices are:

$$\begin{aligned} \boldsymbol{\alpha} &= \boldsymbol{A}_{s0}^{-1}\boldsymbol{\alpha}_s \\ \boldsymbol{\Gamma}_i &= \boldsymbol{A}_{s0}^{-1}\boldsymbol{A}_{si} \\ \boldsymbol{C} &= \boldsymbol{A}_{s0}^{-1}\boldsymbol{C}_s \\ \boldsymbol{\varepsilon}_t &= \boldsymbol{A}_{s0}^{-1}\boldsymbol{\varepsilon}_{st} \end{aligned}$$

In the case of $p = 2$ the reduced form (26) becomes:

$$\boldsymbol{y}_t = (\boldsymbol{\alpha}\boldsymbol{\beta}' + \boldsymbol{I} + \boldsymbol{\Gamma}_1)\boldsymbol{y}_{t-1} - \boldsymbol{\Gamma}_1\boldsymbol{y}_{t-2} + \boldsymbol{C}\boldsymbol{D}_t + \boldsymbol{\varepsilon}_t, \tag{27}$$

A solution for $\boldsymbol{y}_t$ can be obtained by recursion forward from known initial conditions, $\boldsymbol{y}_0$,$\boldsymbol{y}_{-1}$ and by random numbers from the distribution of $\boldsymbol{\varepsilon}_t$ for $t = 1, 2, ..., T$.

In the simulated response to a price shock, second order dynamics was used $(p = 2)$.

The calibration of the matrix with simulated coefficients $\boldsymbol{A}_{s0}$:

$$\boldsymbol{A}_{s0} = \begin{pmatrix} 1 & -0.7 & 0 & -0.15 & 0.7 \\ -0.45 & 1 & 0 & -0.20 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -\psi_{pi,\pi} & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}. \tag{28}$$

The first row shows that the coefficients of wage growth (Δw_t) and import price growth (Δpi_t) in the Δq equation are 0.7 and 0.15. The sum is 0.8, which contributes to a relatively large impact response of inflation. The coefficients in the second row (Δw_t equation), contribute in the same direction. The third row says that the responses have been simulated with the rate of unemployment as an exogenous time series, in order to match the simulations of the Blanchard and Bernanke model.

As mentioned above, the model includes a relationship between δpi_t and and inflation that can be used to mimic a response in the foreign exchange market to inflation. However the simulated response function was done with $\psi_{pi,\pi} = 0$ in fourth row, corresponding to the exogenous process for pi_t in equation (10) in the main text.

The calibration of the matrix $\boldsymbol{A}_{s1}$ which is multiplied by $\Delta \boldsymbol{y}_{t-1}$:

$$\boldsymbol{A}_{s1} = \begin{pmatrix} 0.15 & 0.2 & 0 & 0 & 0 \\ 0 & -0.08 & 0 & 0 & 0 \\ 0 & 0 & 0.4 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0 \\ 0 & 0 & 0 & 0 & 0.85 \end{pmatrix} \tag{29}$$

This calibration adds some persistence to the wage-price adjustments, i.e., in addition to the dynamics generated by the equilibrium correction part of the system. Finally the calibration of the matrix with cointegration coefficients $\boldsymbol{\beta}$ and the equilibrium correction coefficients $\boldsymbol{\alpha}$:

$$\boldsymbol{\beta} = \begin{pmatrix} 1 & 0.86 & 0 \\ -1 & 1 & 0 \\ 0 & -1.5 & 1 \\ 0 & 0.14 & 0 \\ 1 & -1 & 0 \end{pmatrix} \tag{30}$$

$$\boldsymbol{\alpha}_s = \begin{pmatrix} -0.09 & 0 & 0 \\ 0 & -0.06 & 0 \\ 0 & 0 & -0.10 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{31}$$

B Bernake and Blanchard's inflation model

Using the same notation as in Blanchard and Bernanke (2023), BB, for coefficients and variables, the wage equation is written as:

$$w_t = p_t^e + \omega_t^A + \beta x_t. \tag{32}$$

BB call ω_t^A the real-wage ambition (or target). It is given by the equation:

$$\omega_t^A = \alpha \omega_{t-1}^A + (1-\alpha)(w_{t-1} - p_{t-1}) + z_{wt}. \tag{33}$$

Re-normalize (32) on ω_t^A and insert in (33):

$$\omega_t^A = \alpha(w_{t-1} - p_{t-1}^e - \beta x_{t-1}) + (1-\alpha)(w_{t-1} - p_{t-1}) + z_{wt}$$

and use this to eliminate ω_t^A in (32), which becomes:

$$w_t = p_t^e + \alpha(w_{t-1} - p_{t-1}^e - \beta x_{t-1}) + (1-\alpha)(w_{t-1} - p_{t-1}) + z_{wt} + \beta x_t$$

which can be written as:

$$\begin{aligned} w_t - w_{t-1} &= p_t^e + \alpha w_{t-1} - \alpha p_{t-1}^e - \alpha\beta x_{t-1} - \alpha w_{t-1} - (1-\alpha)p_{t-1} + z_{wt} + \beta x_t \\ &= p_t^e - \alpha p_{t-1}^e - (1-\alpha)p_{t-1} + \beta x_t - \alpha\beta x_{t-1} + z_{wt} \\ &= (p_t^e - p_{t-1}) - \alpha(p_{t-1}^e - p_{t-1}) + \beta(x_t - \alpha x_{t-1}) + z_{wt}. \end{aligned} \tag{34}$$

The price-setting equation in the model is to start with the static equation for p_t:

$$p_t = w_t + z_{pt} \tag{35}$$

(z_{pt} is a price level shock), but BB replaced it with the differenced version:

$$\Delta p_t = \Delta w_t + \Delta z_{pt} \tag{36}$$

Two equations define short-term price expectation, p_t^e, and long-term inflation expectations, π_t^*:

$$p_t^e - p_{t-1} = \delta\pi_t^* + (1-\delta)(p_{t-1} - p_{t-2}) \tag{37}$$

$$\pi_t^* = \gamma\pi_{t-1}^* + (1-\gamma)(p_{t-1} - p_{t-2}) \tag{38}$$

Note that since $p_{t-1} - p_{t-2} \equiv \Delta p_{t-1}$ equation (38) can be rewritten as

$$\pi_t^* - \pi_{t-1}^* = (1-\gamma)\left(\Delta p_{t-1} - \pi_{t-1}^*\right) \tag{39}$$

which is the adaptive expectations formulation.

In working with this model, we found it useful to define the short-term expectation error:

$$e_{pt} = p_t^e - p_{t-1},$$

and use that variable to express (34) as:

$$w_t - w_{t-1} = e_{pt} - \alpha e_{pt-1} + \alpha(p_{t-1} - p_{t-2}) + \beta(x_t - \alpha x_{t-1}) + z_{wt}$$

Next, use (38), and the definition $p_t^e - p_{t-1} = e_{pt}$, to eliminate π_t^* from (37):

$$e_{pt} = \delta\gamma\pi_{t-1}^* + (1-\delta\gamma)(p_{t-1} - p_{t-2})$$

Introducing $\Delta w_t = w_t - w_{t-1}$ and $\Delta p_{t-1} = p_{t-1} - p_{t-2}$ in the two last equations, and noting that (36) is the price-equation, the full model can be written as :

$$\Delta p_t - \Delta w_t = \Delta z_{pt} \tag{40}$$

$$\Delta w_t - e_{pt} = -\alpha e_{pt-1} + \alpha\Delta p_{t-1} + \beta(x_t - \alpha x_{t-1}) + z_{wt} \tag{41}$$

$$e_{pt} = \delta\gamma\pi_{t-1}^* + (1-\delta\gamma)\Delta p_{t-1} \tag{42}$$

$$\pi_t^* = \gamma\pi_{t-1}^* + (1-\gamma)\Delta p_{t-1} \tag{43}$$

By using (40) for period $t-1$, Δp_{t-1} can be eliminated, and the model can be written more compactly as:

$$\Delta w_t - e_{pt} = -\alpha e_{pt-1} + \alpha\Delta w_{t-1} + \beta(x_t - \alpha x_{t-1}) + z_{wt} + \alpha\Delta z_{pt-1}, \tag{44}$$

$$e_{pt} = \delta\gamma\pi^*_{t-1} + (1-\delta\gamma)\Delta w_{t-1} + (1-\delta\gamma)\Delta z_{pt-1}, \tag{45}$$

$$\pi^*_t = \gamma\pi^*_{t-1} + (1-\gamma)\Delta w_{t-1} + (1-\gamma)\Delta z_{pt-1} \tag{46}$$

The system determines Δw_t, e_{pt} and π^*_t for given initial conditions, and conditional on exogenous time series x_t, z_{wt} and Δz_{pt-1}. Dynamic stability of the endogenous time series variables depends on the eigenvalues of the system::

$$r_1 = 1, r_2 = \gamma(1-\delta), r_3 = \alpha.$$

Hence there is a unit-root (which does not depend on the values of the expectation parameters δ and γ). The system is not globally asymptotically dynamically stable.

Finally we write the system in the way it is reported in the main text. We re-write the wage equation (41) by noting that from (42):

$$\begin{aligned} e_{pt} - \alpha e_{pt-1} &= \delta\gamma\pi^*_{t-1} + (1-\delta\gamma)\Delta p_{t-1} - \alpha\delta\gamma\pi^*_{t-2} - \alpha(1-\delta\gamma)\Delta p_{t-2} \\ &= \delta\gamma(\pi^*_{t-1} - \alpha\pi^*_{t-2}) + (1-\delta\gamma)(\Delta p_{t-1} - \alpha\Delta p_{t-2}) \end{aligned}$$

so that the wage equation can be expressed as:

$$\begin{aligned} \Delta w_t &= e_{pt} - \alpha e_{pt-1} + \alpha\Delta p_{t-1} + \beta(x_t - \alpha x_{t-1}) + z_{wt} \\ &= \delta\gamma(\pi^*_{t-1} - \alpha\pi^*_{t-2}) + (1-\delta\gamma+\alpha)\Delta p_{t-1} - (1-\delta\gamma)\alpha\Delta p_{t-2} + \beta(x_t - \alpha x_{t-1}) + z_{wt} \end{aligned} \tag{47}$$

This equation contains the catch-up parameter α. Setting $\alpha = 1$ (maximum catch-up) implies that only the change in long-run inflation expectations (π^*) affects wage growth.

De-anchoring of inflation expectations is represented by decreases in either δ or γ. We see that a decrease in $\delta\gamma$ increases the absolute values of the coefficients of the long-turn inflation.

Since we have eliminated e_{pt}, the system can we written as:

$$\begin{aligned} \Delta w_t &= \delta\gamma(\pi^*_{t-1} - \alpha\pi^*_{t-2}) + (1-\delta\gamma+\alpha)\Delta p_{t-1} - (1-\delta\gamma)\alpha\Delta p_{t-2} \\ &\quad + \beta(x_t - \alpha x_{t-1}) + z_{wt} \end{aligned} \tag{48}$$

$$\Delta p_t = \Delta w_t + \Delta z_{pt} \tag{49}$$

$$\pi^*_t = \gamma\pi^*_{t-1} + (1-\gamma)\Delta w_{t-1} + (1-\gamma)\Delta z_{pt-1} \tag{50}$$

which are found in the main text as equation (12)-(14) after replacing the tightness of the labour market variable x_t by the symbol that we use for the rate of unemployment, u_t, and z_{wt} by s_{wt} and z_{pt} by s_{pt} to avoid conflict of notation (z is used for productivity in the main text).

As noted above, the model is not dynamically stable, which is due to the real root of one. Sali (2024) shows that when the system is written with variables in levels, it is a cointegrated I(2) system. Interestingly, the choice of using (36) and not the original static equation (35) is consequential. Sali shows that the system with (35) replacing (36), is $I(0)$. Hence, in this case differencing a static model equation increases the degree of integration from $d = 0$ to $d = 2$, not to $d = 1$.

C Empirical equations for oil price, and world economic activity

Oil price

$$
\begin{aligned}
\Delta po_t \;=\;& \underset{(0.045)}{0.27}\;\Delta po_{t-1} + \underset{(0.00012)}{0.00051}\;\Delta_4\, WAC_t + \underset{(0.065)}{0.53}\;\mathrm{DI}_{1974(1)t} \\
&+ \underset{(0.089)}{0.29}\;\mathrm{II}_{1979(3)t} - \underset{(0.089)}{0.55}\;\mathrm{II}_{1986(1)t} \\
&+ \underset{(0.089)}{0.45}\;\mathrm{II}_{1990(3)t} + \underset{(0.063)}{0.26}\;\mathrm{DI}_{1990(4)t} + \underset{(0.089)}{0.29}\;\mathrm{II}_{1999(2)t} \\
&+ \underset{(0.063)}{0.21}\;\mathrm{DI}_{2003(1)t} - \underset{(0.063)}{0.53}\;(\mathrm{DI}_{2008(4)t} - \mathrm{DI}_{2009(1)t}) \\
&+ \underset{(0.036)}{0.28}\;(\mathrm{SI}_{2014(3)t} - \mathrm{SI}_{2015(1)t} + \mathrm{DI}_{2015(2)t} - \mathrm{DI}_{2016(1)t}) \qquad (51) \\
&- \underset{(0.063)}{0.48}\;\mathrm{DI}_{2020(2)t} + \underset{(0.0061)}{0.011}
\end{aligned}
$$

OLS 1969(1) − 2023(2)	$\hat{\sigma} = 0.09$
AR 1-5 test:	$F(5, 200) = 1.5[0.19]$
ARCH 1-4 test:	$F(4, 210) = 3.42[0.85]$
Normality test:	$\mathrm{Chi}^2(2) = 7.20[0.03]$
Hetero test:	$F(29, 188) = 3.21[0.00]$

World economic activity

$$
\begin{aligned}
WAC_t = {} & \underset{(0.029)}{0.91}\ WAC_{t-1} - \underset{(0.022)}{0.17}\ (WAC_{t-5} - WAC_{t-6} + WAC_{t-7}) \\
& + \underset{(12)}{52}\ \mathrm{DI}_{2015(3)t} + \underset{(14)}{86}\ \mathrm{DI}_{2019(3)t} \\
& + \underset{(14)}{69}\ \mathrm{DI}_{2019(4)t} + \underset{(13)}{56}\ \mathrm{DI}_{2020(3)t} - \underset{(19)}{2.2e+02}\ \mathrm{II}_{2008(4)t} \\
& - \underset{(5.4)}{29}\ \mathrm{SI}_{2004(2)t} - \underset{(9.9)}{33}\ \mathrm{SI}_{2008(3)t} + \underset{(9.6)}{66}\ \mathrm{SI}_{2009(4)t} \\
& + \underset{(17)}{65}\ \mathrm{SI}_{2011(4)t} - \underset{(17)}{65}\ \mathrm{SI}_{2012(1)t} + \underset{(6.2)}{23}\ \mathrm{SI}_{2013(4)t} \\
& - \underset{(6.2)}{23}\ \mathrm{SI}_{2016(1)t} - \underset{(11)}{40}\ \mathrm{SI}_{2020(3)t} + \underset{(11)}{40}\ \mathrm{SI}_{2021(2)t} \\
& + \underset{(3.3)}{6.1} - \underset{(3.3)}{19}\ \mathrm{Seasonal}_t - \underset{(3.2)}{5.9}\ \mathrm{Seasonal}_{t-1} \\
& - \underset{(3.3)}{18}\ \mathrm{Seasonal}_{t-2}
\end{aligned}
$$

OLS 1970(1) − 2023(2)	$\hat{\sigma} = 16.55$
AR 1-5 test:	$F(5, 192) = 1.84[0.11]$
ARCH 1-4 test:	$F(4, 206) = 3.88[0.005]$
Normality test:	$\mathrm{Chi}^2(2) = 1.21[0.55]$
Hetero test:	$F(27, 186) = 0.64[0.92]$

D IV estimation of the model equations for wage, price and productivity

The structure of the multiple equation model shows that Δz_t is an endogenous explanatory variable in wage equation (52). The only other contemporaneous explanatory variable in the equation is Δp_t, which is pre-determined given the structure of the complete model. However, other structures that would imply endogeneity of Δp_t is probably also data admissible.

To investigate robustness with respect to estimation method, equation (52) shows IV-estimation results when Δz_t and Δp_t have been instrumented by six explanatory variables in the two respective model equations. Five of the instrument are lagged, only Δpi_t is contemporaneous.

$$
\begin{aligned}
\Delta w_t \;=\; & -\underset{(0.06)}{0.23}\;\Delta w_{t-1} + \underset{(0.17)}{0.40}\;\Delta z_t + \underset{(0.10)}{0.28}\;\Delta q_{t-1} + \underset{(0.12)}{0.67}\;\Delta p_t \\
& + \underset{(0.009)}{0.032}\;1/U_{t-3} - \underset{(0.016)}{0.084}\;[w - q - 0.82z]_{t-1} \\
& + \underset{(0.0065)}{0.03}\;II_{2000(1)t} + \underset{(0.0047)}{0.023}\;DI_{2008(4)t} + \underset{(0.0045)}{0.017}\;DI_{2012(4)t} \\
& + \underset{(0.0083)}{0.046}\;II_{2020(2)} - \underset{(0.0018)}{0.0018}
\end{aligned}
\tag{52}
$$

$$
\begin{array}{ll}
\hline
\text{IVE } 1967(1) - 2023(2) & \hat{\sigma}100 = 0.63 \\
\text{Sargan-IV:} & \chi^2(4) = 4.06[0.40] \\
\text{Additional instruments :} & \\
(z - 1.2(w - q) + 0.07pi)_{t-1}, \Delta pi_t, \Delta pi_{t-1} & \\
(p - 0.96q - 0.04pi + tra)_{t-1}, \Delta q_{t-2}, \Delta q_{t-3} & \\
\hline
\end{array}
$$

The results show that the coefficients of Δp_t and Δz_t, the two endogenous explanatory variables, are somewhat inflated compared to the OLS estimates, as often is the case. The specification test (4 over-identifying instruments) is insignificant, in support of the validity of the instruments.

In the price equation (18), Δz_t is an endogenous explanatory variable. The IV estimates in (53) shows only minor deviations from the OLS estimates reported in the main text.

$$
\begin{aligned}
\Delta q \;=\; & \underset{(0.021)}{0.22}\;\Delta_2 q_{t-2} - \underset{(0.077)}{0.20}\;\Delta z_t + \underset{(0.009)}{0.033}\;\Delta pi_{t-2} \\
& + \underset{(0.0011)}{0.0069}\;\Delta_2 po_t + \underset{(0.011)}{0.027}\;\Delta capu_{t-2} \\
& - \underset{(0.01)}{0.11}\;[q_{t-1} - 0.69 w_{t-1} + 0.21(z - pi)_{t-1} \\
& \qquad\qquad + 0.04(po_{t-1} - (SI_{72(1)t} + SI_{86(2)t} + SI_{99(1)t})] \\
& + \underset{(0.003)}{0.013}\;\mathrm{II}_{98(1)t} + \underset{(0.002)}{0.019}
\end{aligned}
\tag{53}
$$

$$
\begin{array}{ll}
\hline
\text{IVE } 1967(4) - 2023(2) & \hat{\sigma}100 = 0.69 \\
\text{Sargan-IV:} & \chi^2(5) = 4.43[0.49] \\
\text{Additional instruments :} & \\
(w - 0.82z - q)_{t-1}, \Delta w_{t-1}, \Delta q_{t-1}, (1/u)_{t-3} & \\
(z - 1.2(w - q) + 0.07pi)_{t-1}, \Delta pi_{t-2} & \\
\hline
\end{array}
$$

When it gets to the productivity growth equation, the complete model implies that $\Delta(w-q)_t$ is an endogenous explantory variable. In the IVE-estimation, we de-restricted $\Delta(w - q)_t$ to better see the robustness of the two endogenous explanatory variables with respect to IV-estimation. The results in equation (54) show that both variables are significant. Although there is a difference in the magnitudes of the two coefficients, the more concise representation

$\Delta(w-q)_t$ is defensible also based on these results.

$$\begin{array}{rcl}\Delta z_t & = & \underset{(0.12)}{0.23}\ \Delta w_t \ \underset{(0.18)}{-0.34}\ \Delta q_t \ - \ \underset{(0.021)}{0.058}\ \Delta pi_{t-1} \ + \ \underset{(0.0018)}{0.0081}\ u_t \\ & & - \ \underset{(0.016)}{0.1}\ [z_{t-1} - 1.2(w-q)_{t-1} + 0.07pi_{t-1}] \ - \ \underset{(0.0032)}{0.01} \\ \hline & & \text{IVE } \ 1967(4) - 2023(2) \hat{\sigma} 100 = 0.67 \\ & & \text{Sargan-IV:} \chi^2(5) = 1.02[0.96] \\ & & \text{Additional instruments :} \\ & & (w - 0.82z - q)_{t-1}, \Delta q_{t-1}, (1/u)_{t-3} \\ & & (p - 0.96q - 0.04pi + tra)_{t-1}, \Delta_3 \Delta tra_t, \Delta_2 \Delta q_2, \\ & & (q_{t-1} - 0.69w_{t-1} + 0.21(z-pi)_{t-1} \\ & & +0.04(po_{t-1} - (SI_{72(1)t} + SI_{86(2)t} + SI_{99(1)t}) \quad) \\ \hline \end{array} \tag{54}$$

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